Nucleosynthesis and Neutrinos in Core-collapse Supernovae

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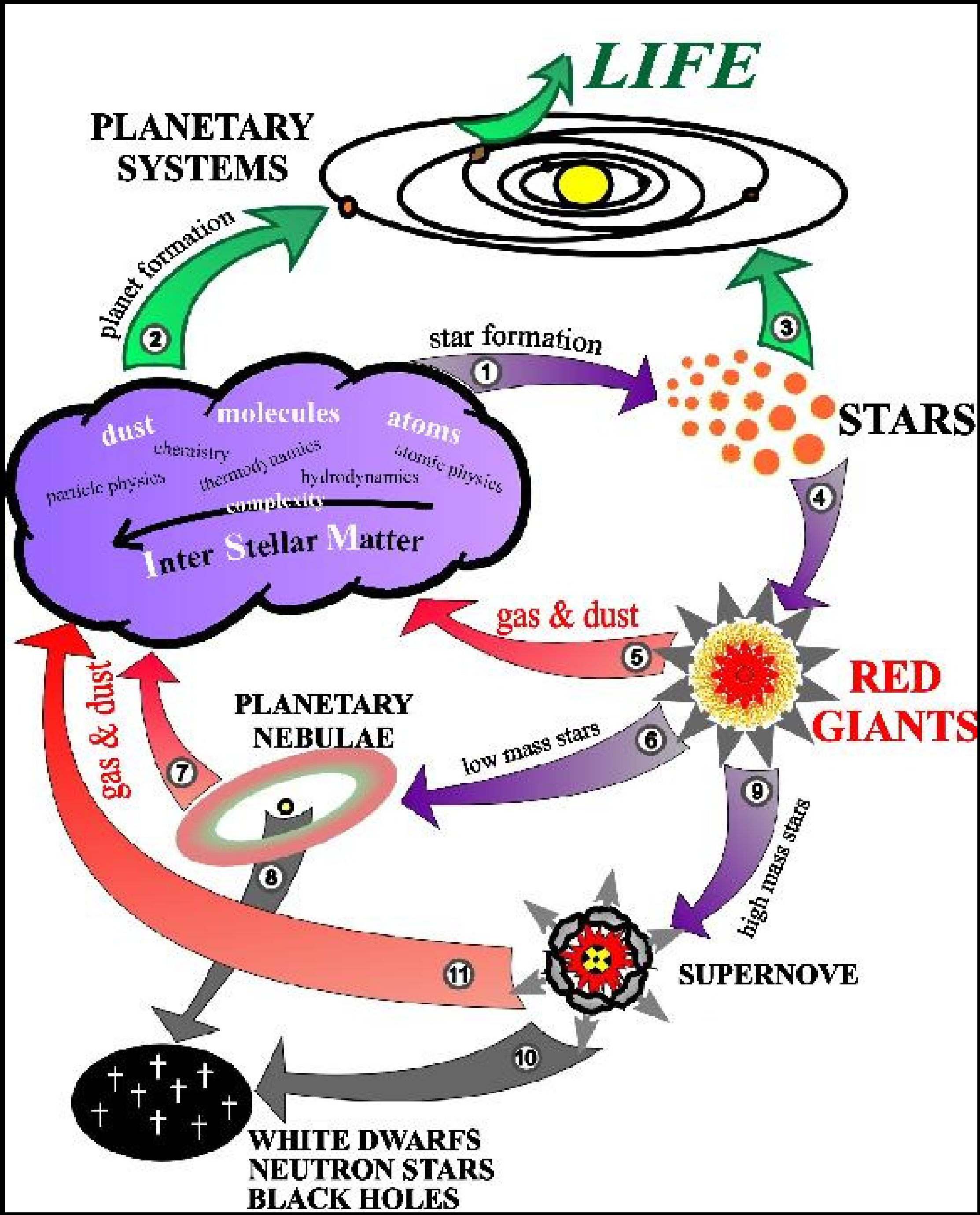
Outline

- Nucleosynthesis sites
- Observational abundance trends
  - Heavy elements
  - Fe-group elements
- Supernova nucleosynthesis and neutrinos
  - Explosion models
  - Proton-to-neutron ratio
  - Neutrino-induced nucleosynthesis, νp-process



LIFE
PLANETARY SYSTEMS
planet formation
star formation
STARS
dust
molecules
atoms
chemistry
thermodynamics
atomic physics
particle physics
hydrodynamics
complexity
Inter Stellar Matter
gas & dust
RED GIANTS
gas & dust
PLANETARY NEBULAE
low mass stars
high mass stars
SUPERNOVE
WHITE DWARFS
NEUTRON STARS
BLACK HOLES

Nucleosynthesis Sites

Massive stars (M>10Msun) and SNe II

- Synthesis of the nuclear species from O to Zn
- Heavy elements: r-process, p-process, νp-process

Red giants (AGB stars)

- Carbon
- S-process elements

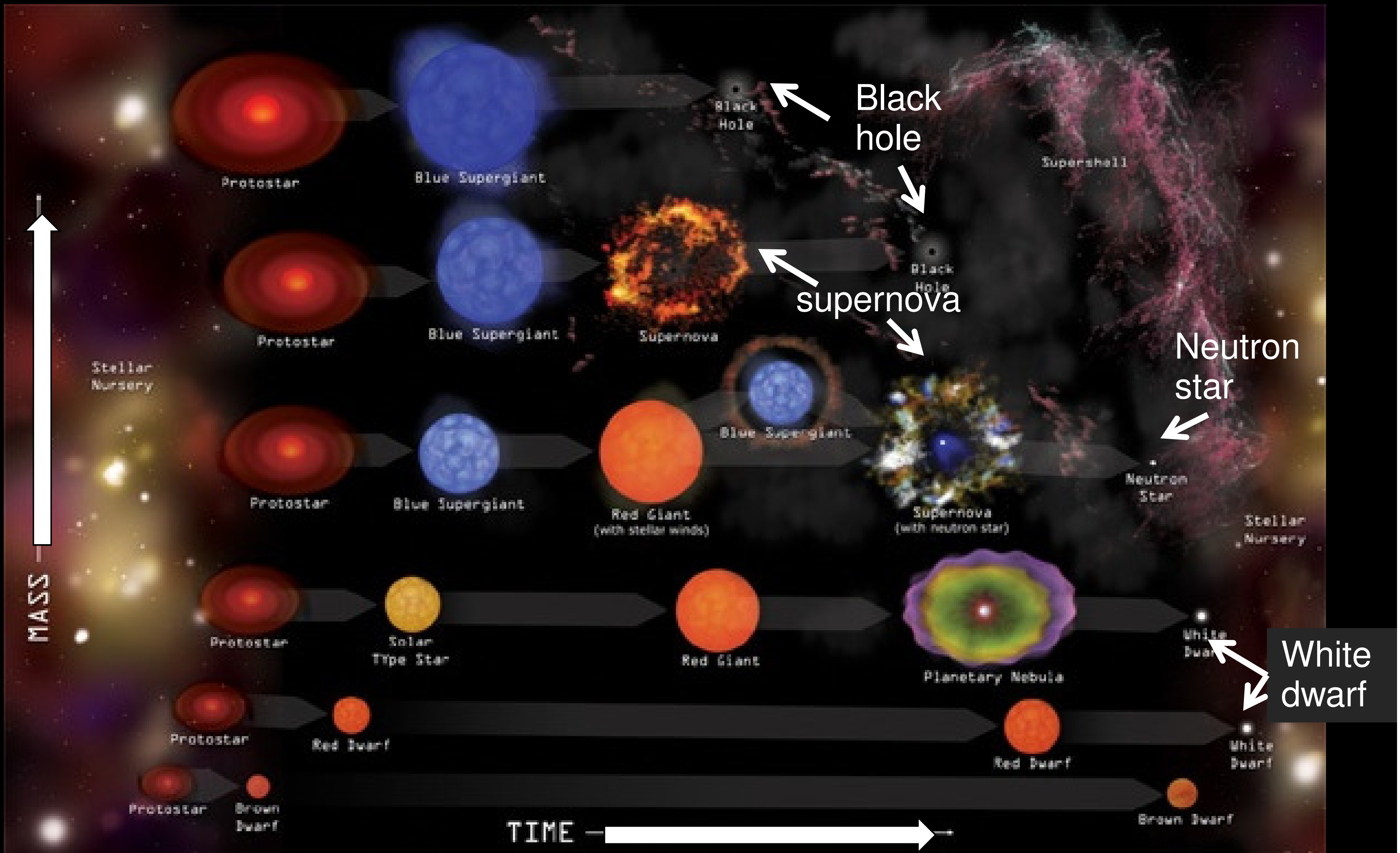
SNe Ia

- ½ to 2/3 of iron peak nuclei not produced by SNe II

Novae

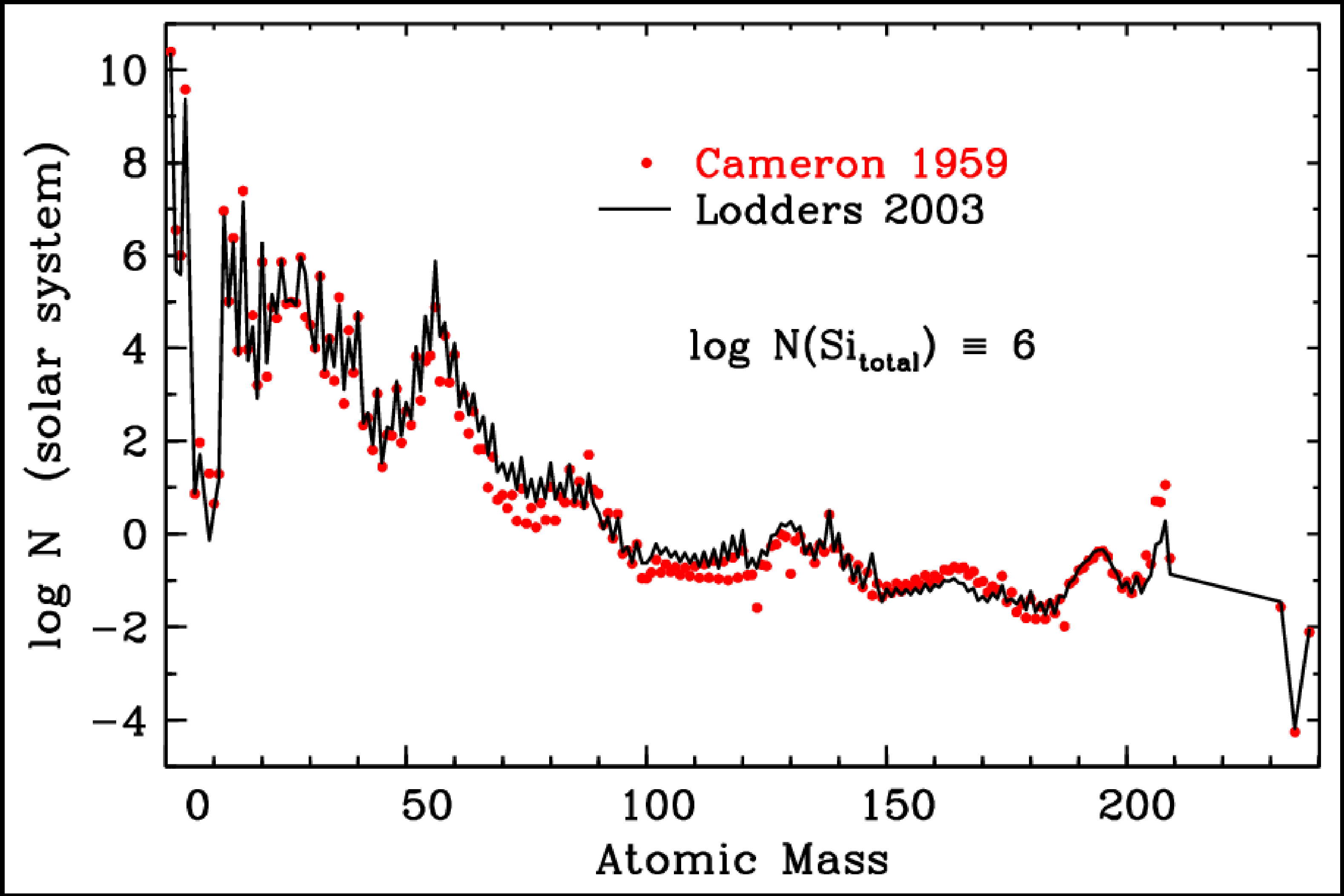
- May be significant source of ^{13}C, ^{15}N, and ^{17}O in galactic matter
- May be source of presolair grains

Stellar Lifetimes and Metal-Poor Stars



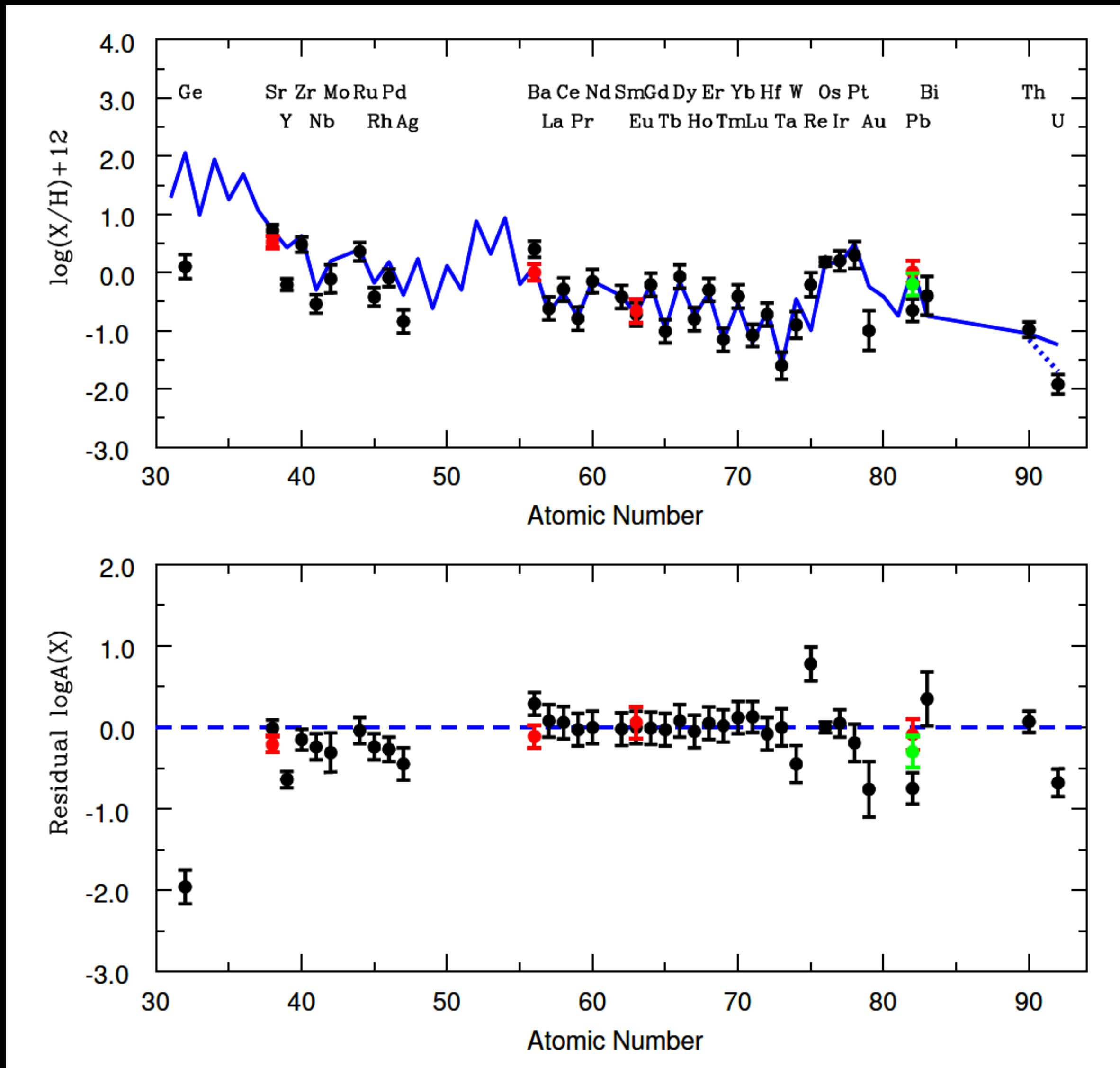
Solar System Abundances

Goal: understanding the solar chemical composition



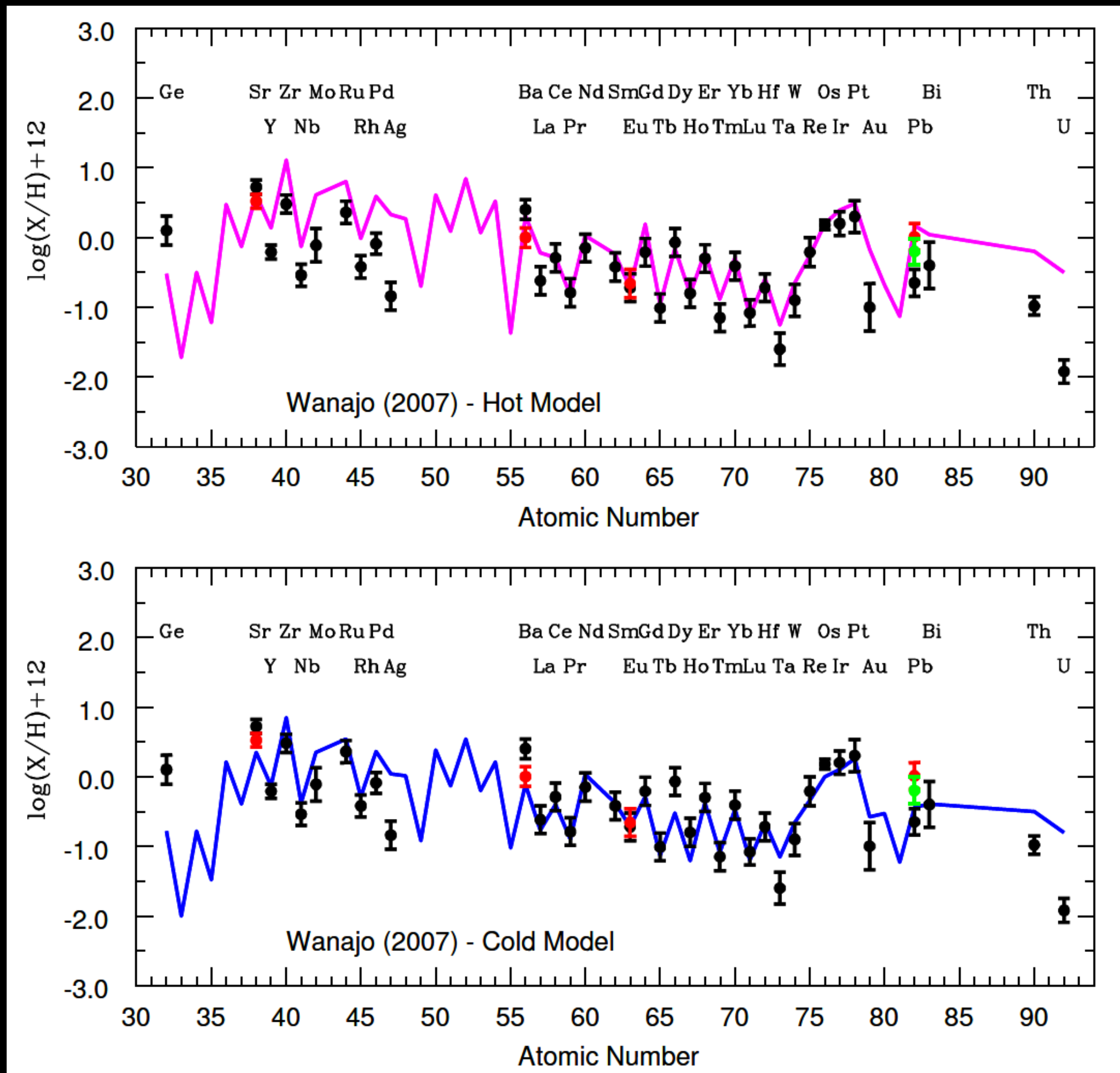
A “complete” pattern

Scaled solar system r-process



Mello et al (2013)

Comparison to theoretical models



Mello et al (2013)

Heavy elements in r-rich stars

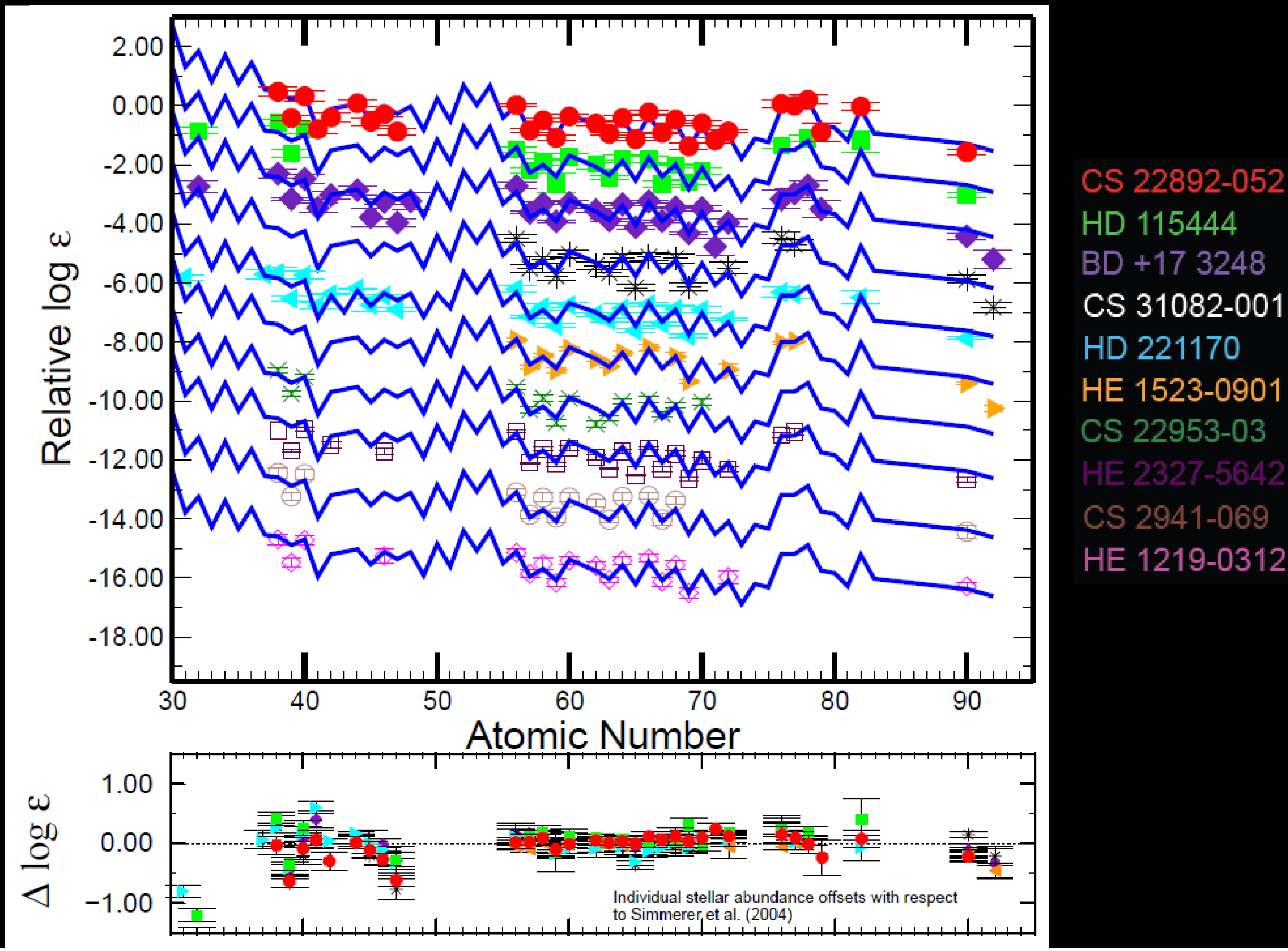


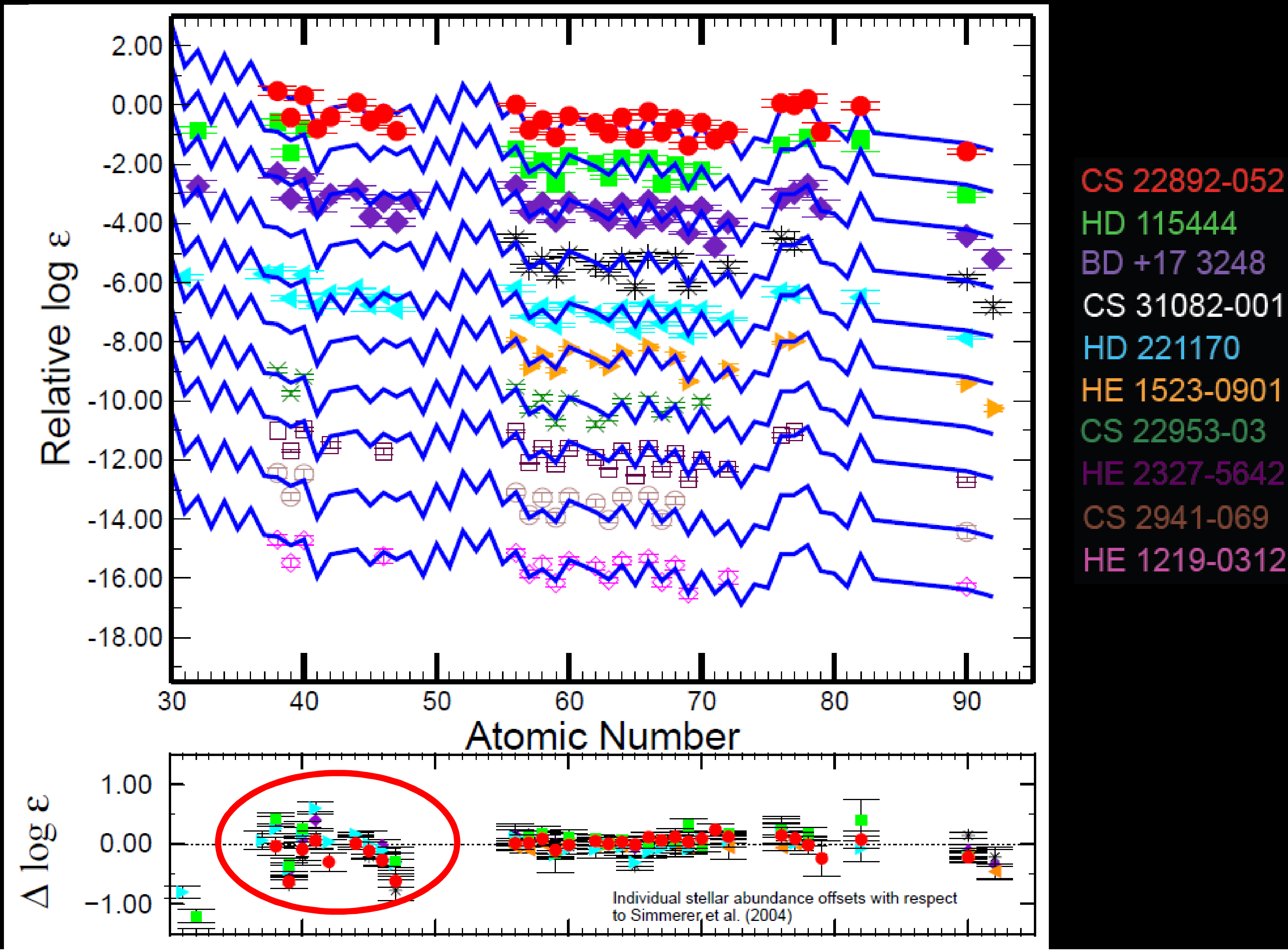
Figure: John Cowan (2011)

Observational Trends

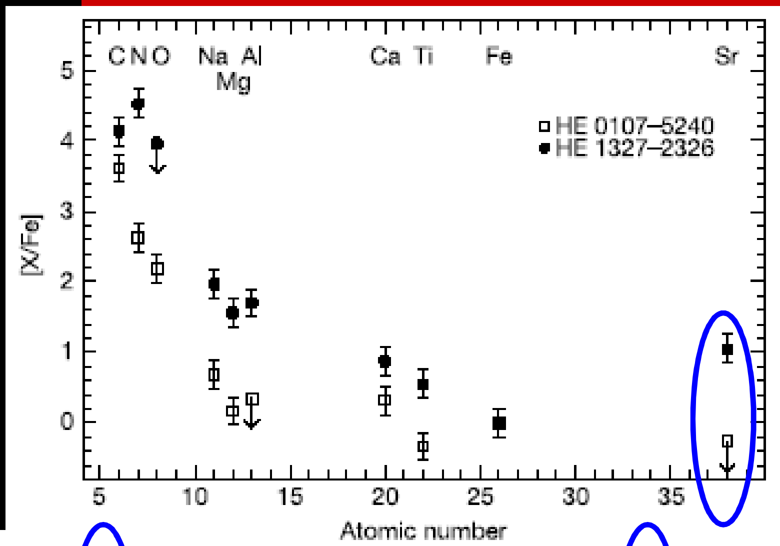
- Heavy n-capture elements
  - Seems robust (and understood)

Heavy elements in r-rich stars

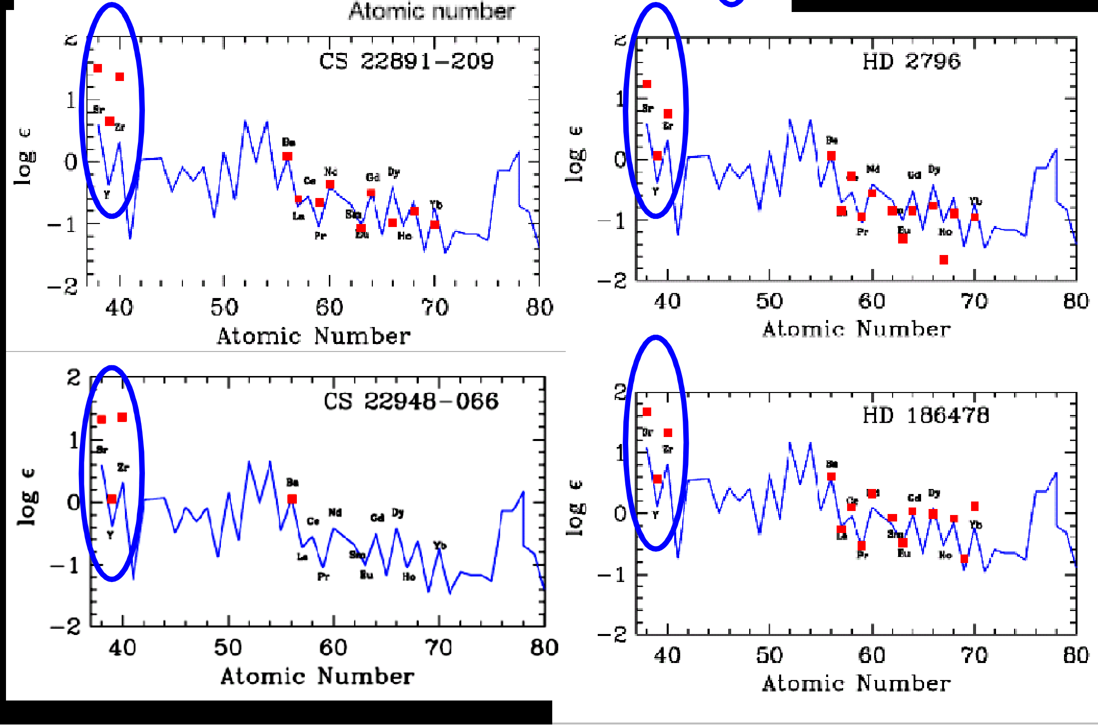
Figure: John Cowan (2011)

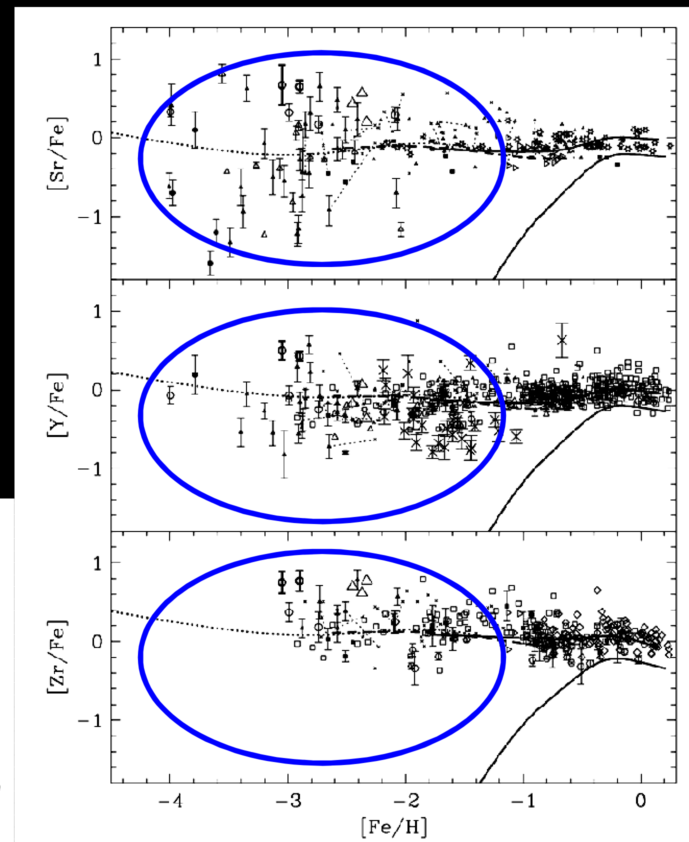


Light n-capture elements



Frebel et al (2005)





Travaglio et al (2007)

Scaled solar system r-process

François et al (2007)

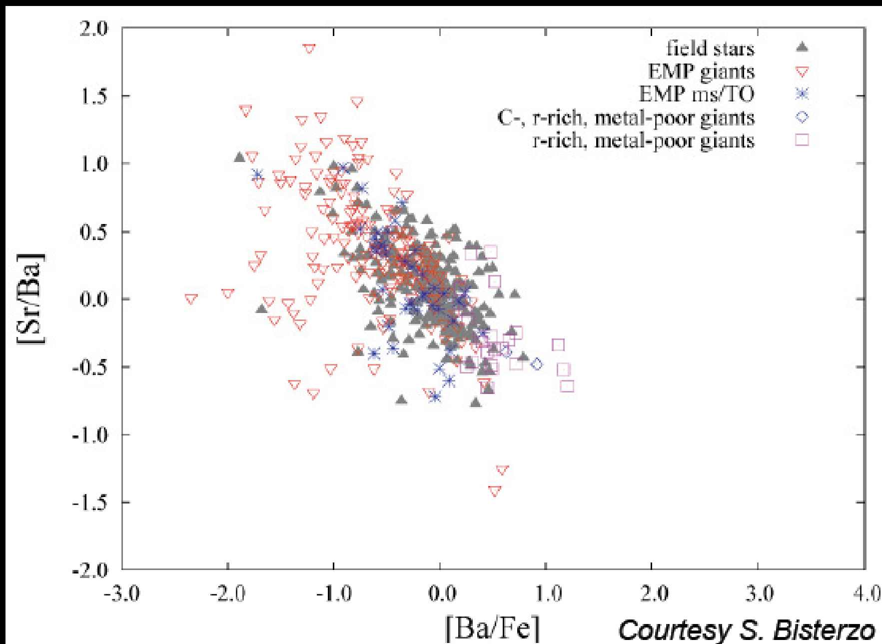
Observational Trends

- Heavy n-capture elements
  - Seems robust (and understood)

- Light n-capture elements
  - Confusing situation

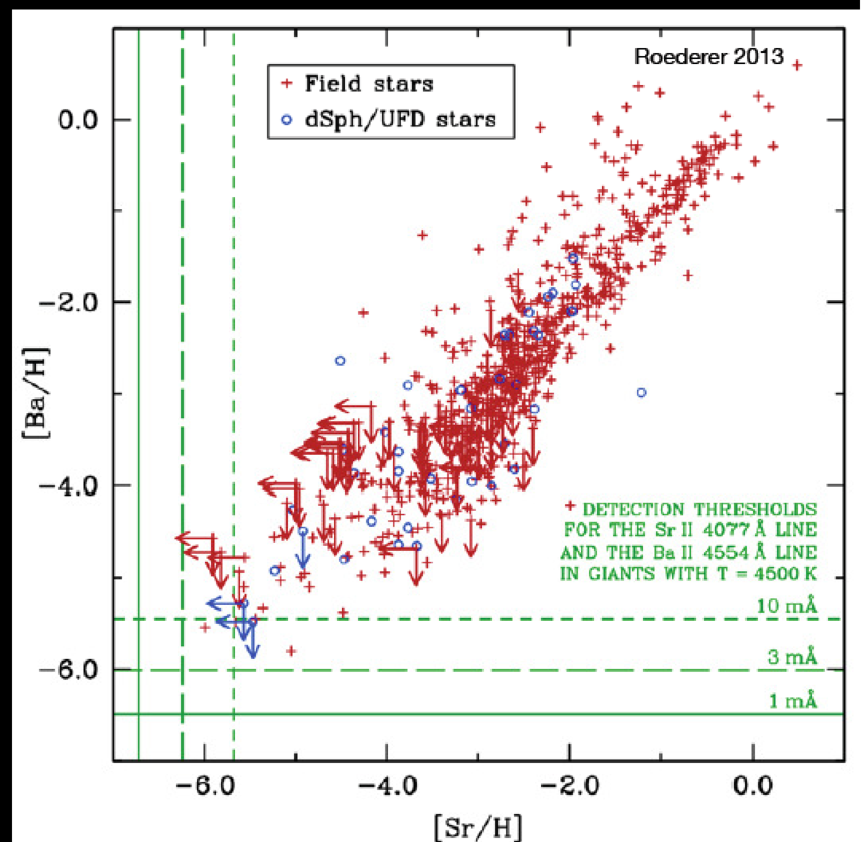
Sr and Ba in metal-poor stars

Figure: S. Bisterzo
Data: SAGA (Suda et al 2008)



Courtesy S. Bisterzo

No known metal-poor star without neutron-capture elements?



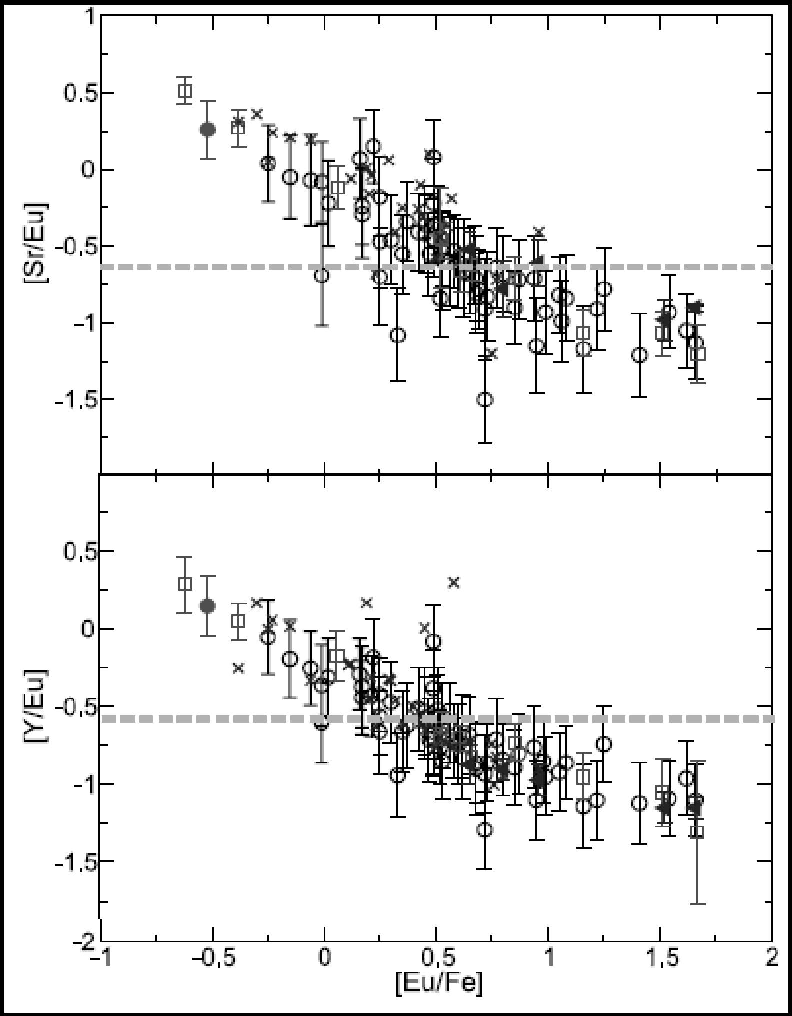
Roederer 2013

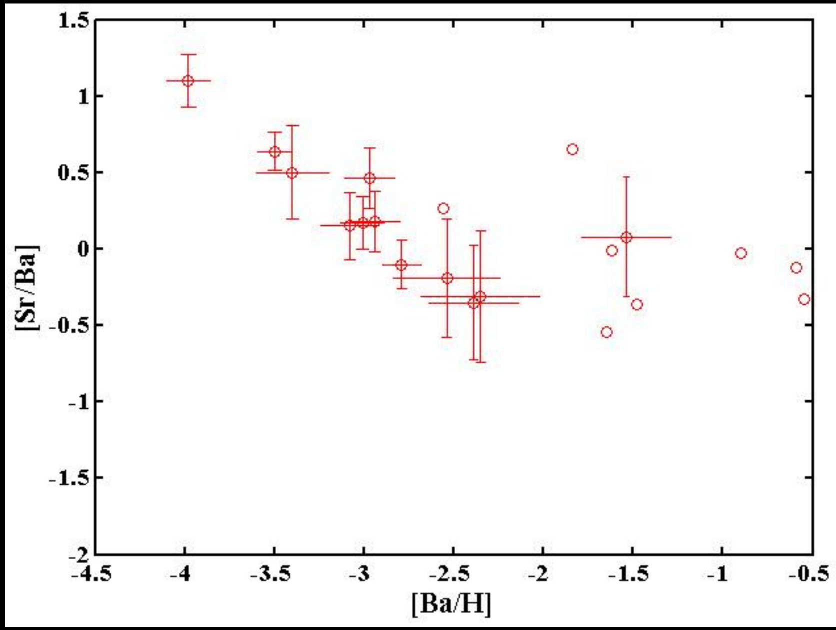
large scatter in Sr/Ba at low metallicities

➔ evidence for a independent process producing Sr but not Ba at low metallicities.

Sr, Y, Zr

Montes et al (2007)





Banerjee & Frohlich, in prep

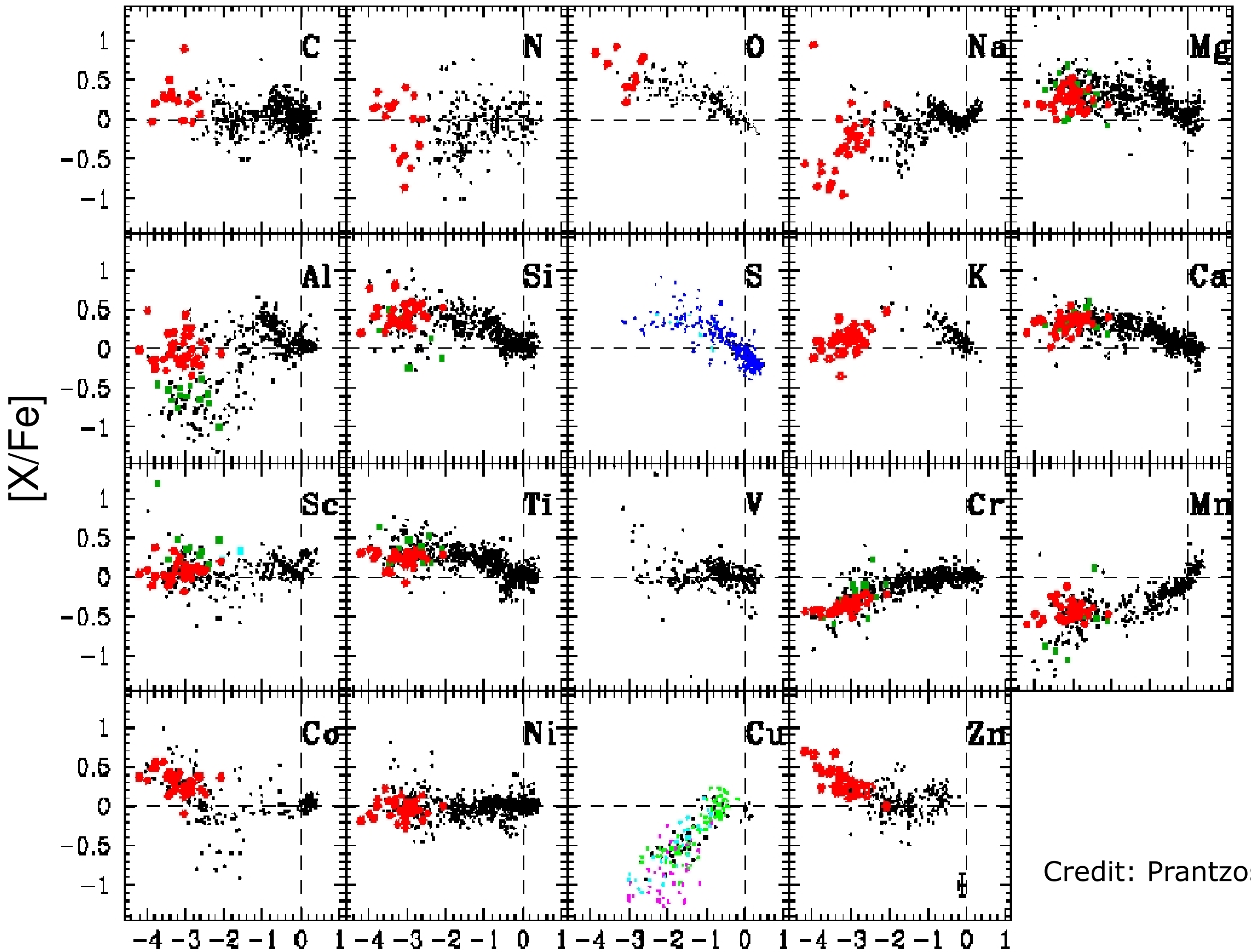
➔ Non-correlation of Sr, Y, Zr, Pd and Ag in metal-poor halo stars with Eu nor Ba

Observational Trends

- Heavy n-capture elements
  - Seems robust (and understood)

- Light n-capture elements
  - ~~Confusing situation~~ Interesting situation
  - Large scatter
  - Various processes proposed: LEPP, νp-process, weak r-process, ???

Trends with Metallicity

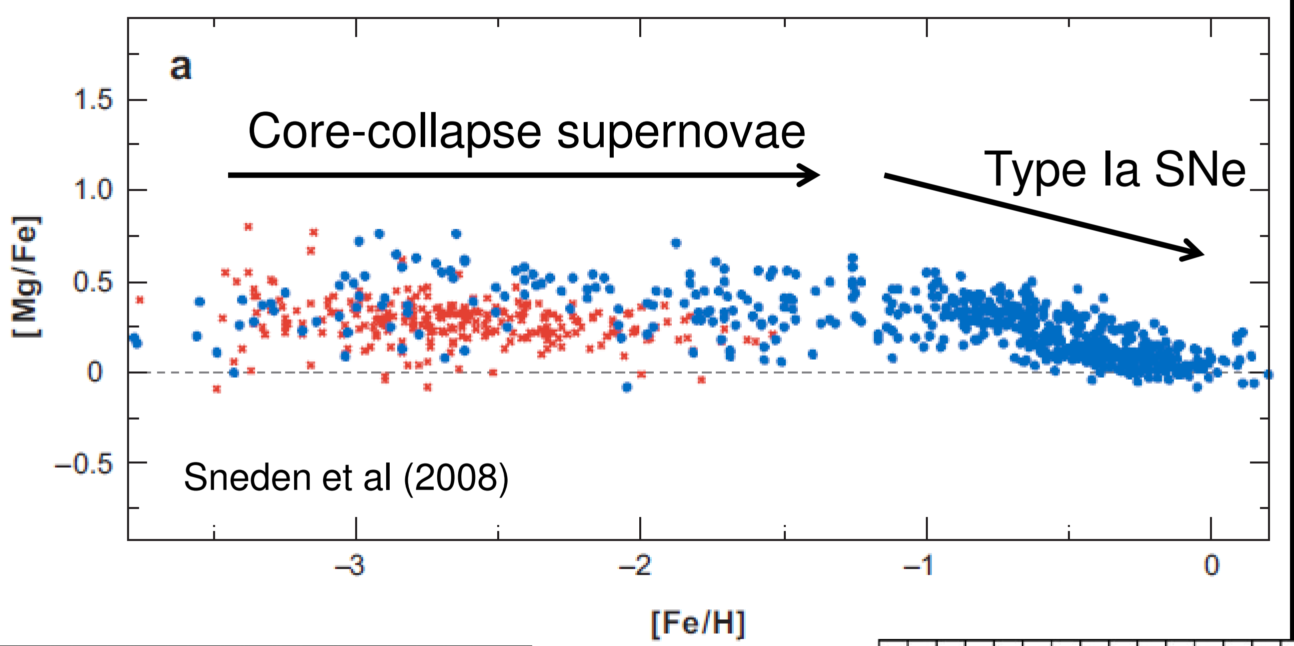


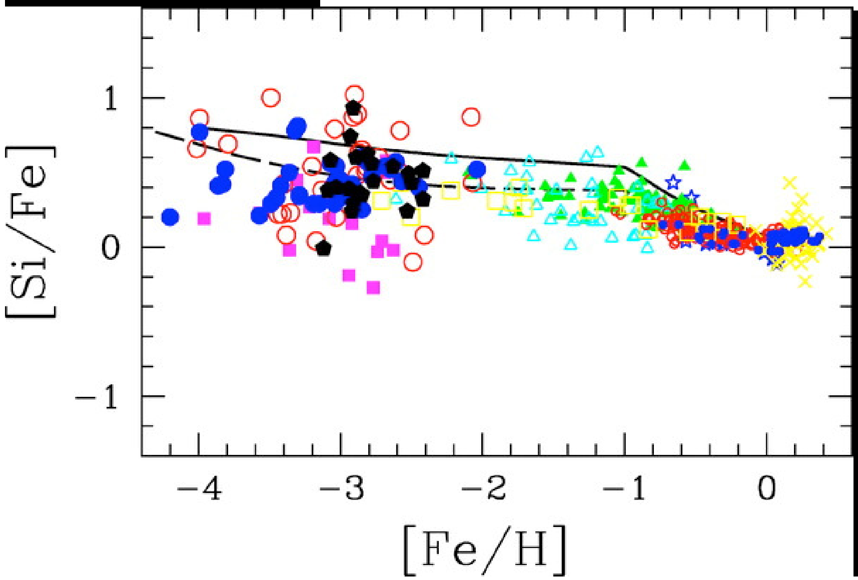
$[X/Fe] = \log_{10}[(X/Fe)/(X/Fe)_\odot]$

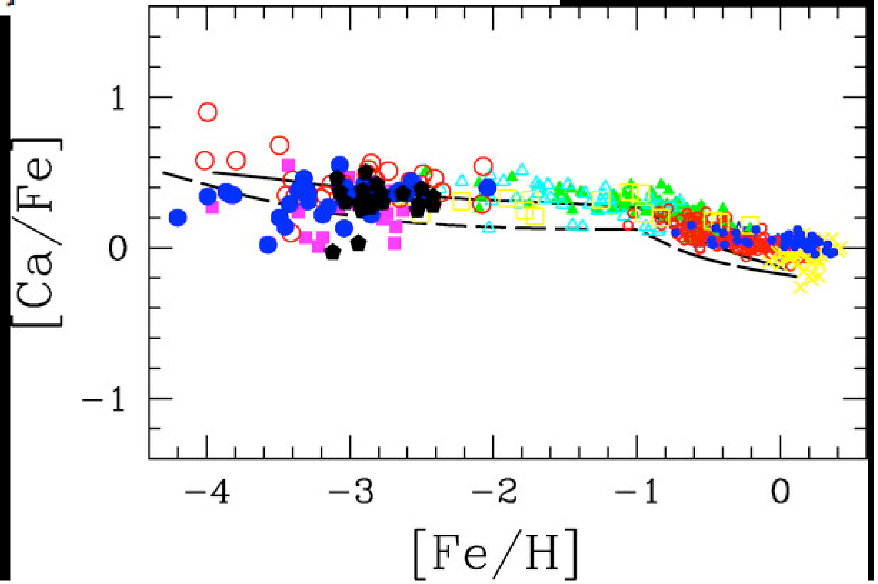
Credit: Prantzos

Trends with Metallicity

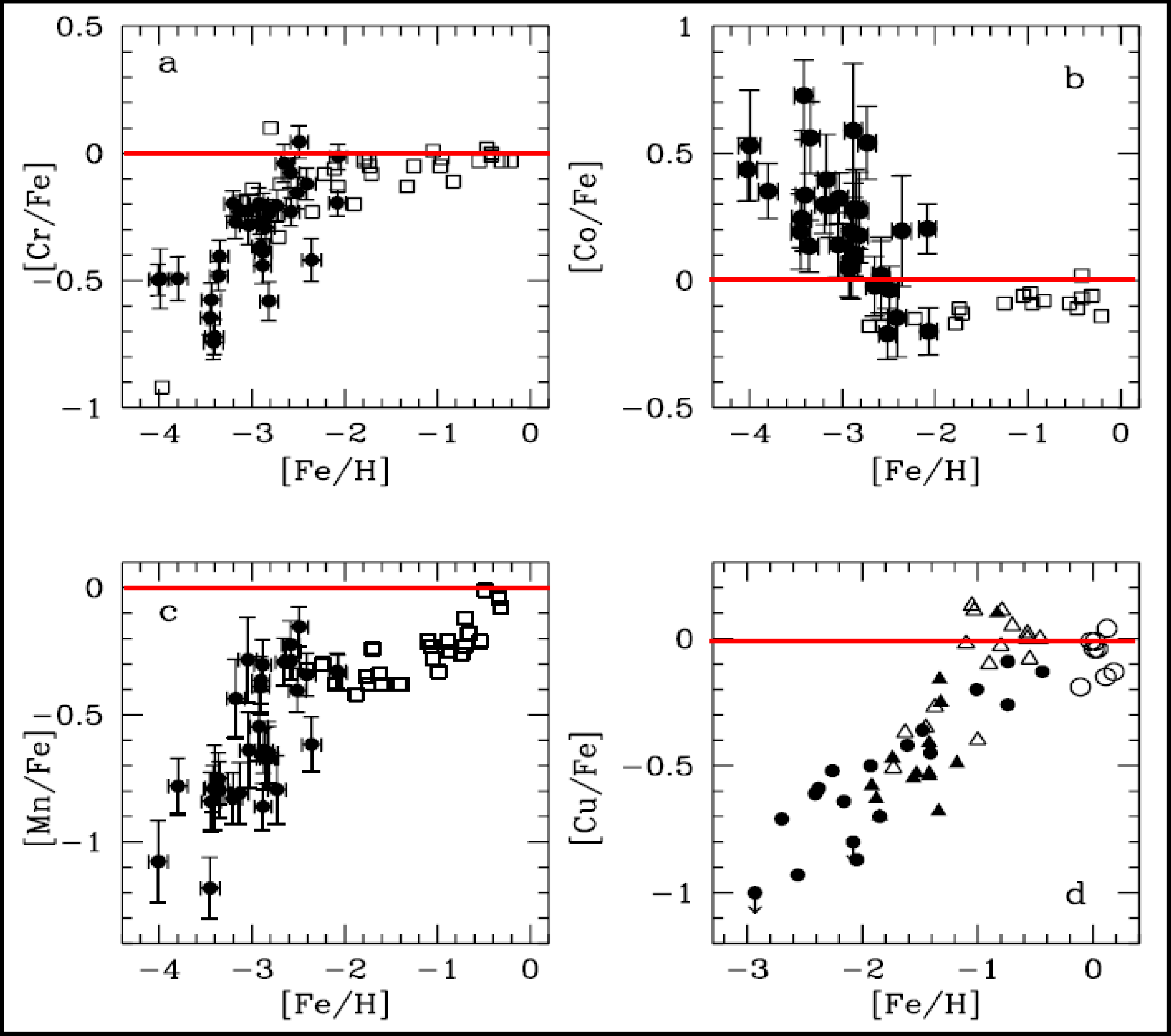
Kobayashi et al. 2006







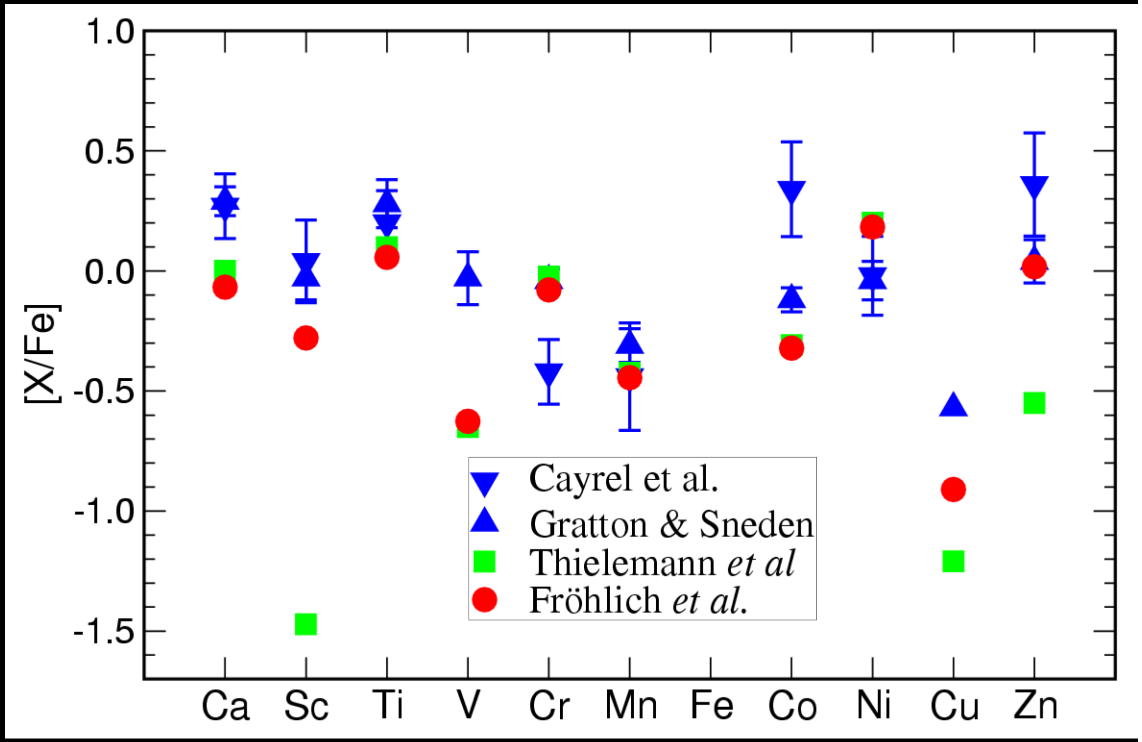
Fe-peak elements



McWilliam 1997

Fe-group nucleosynthesis

- Explosive Si-burning
- All reactions in equilibirum
  → Y=Y(Yn, Yp, ρ, T)
- Max temp
  → amount of unburned material (Si)
- Max density
  → amount of Fe versus free p and α



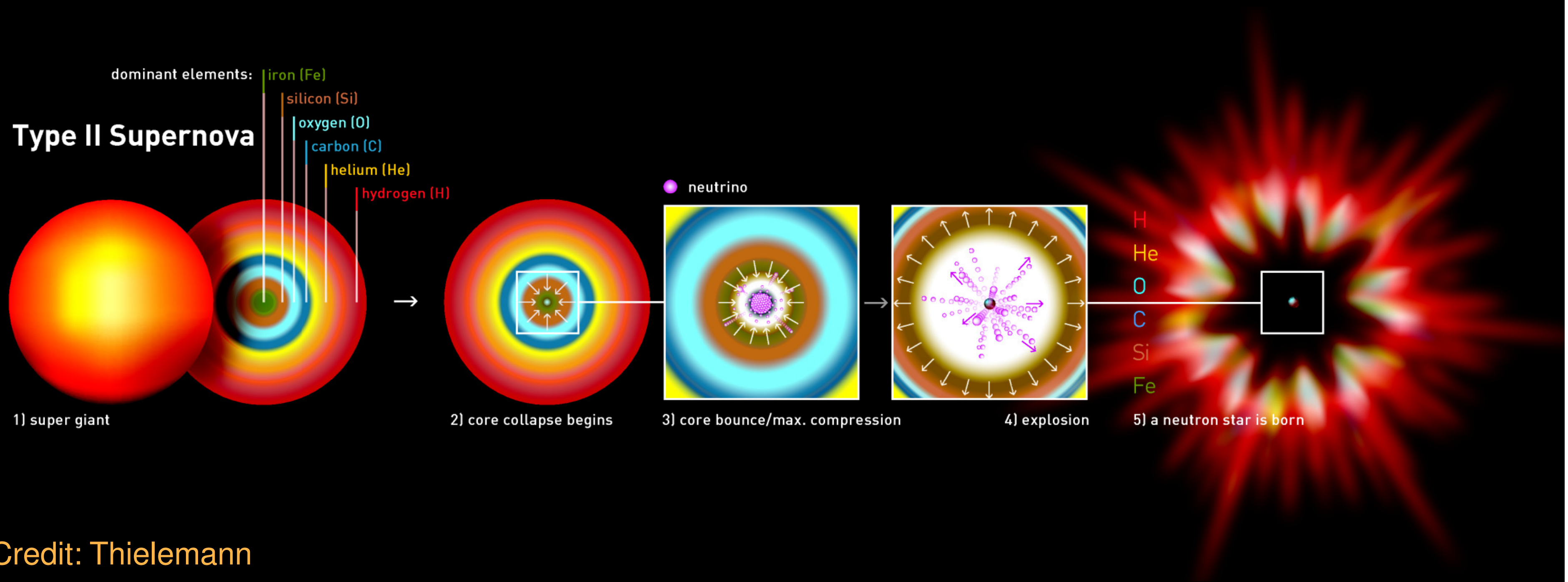
Neutrino-interactions matter; the electron fraction Ye matters

$[X/Fe] = \log_{10} [(X/Fe)/(X/Fe)_{sol}]$

Supernova Nucleosynthesis

- Oxygen and alpha-elements (Ne, Mg, Ca)
  - (γ,α) reactions on O and Ne
- Silicon, sulfur, calcium
  - Explosive oxygen burning through $^{16}O + {}^{16}O$
- Fe-group elements (Ti to Zn, mainly ^{56}Ni)
  - Explosive nucleosynthesis through (α,γ)
- Heavy elements (r-process??)
- Weak s-process (core He-burning)
- “Lighter heavy elements” (νp-process)
- p-nuclei (γ-process)
- 11B, 19F, 138La, 180Ta (ν-process)
  - (ν,ν') and (ν_e,e^-) reactions

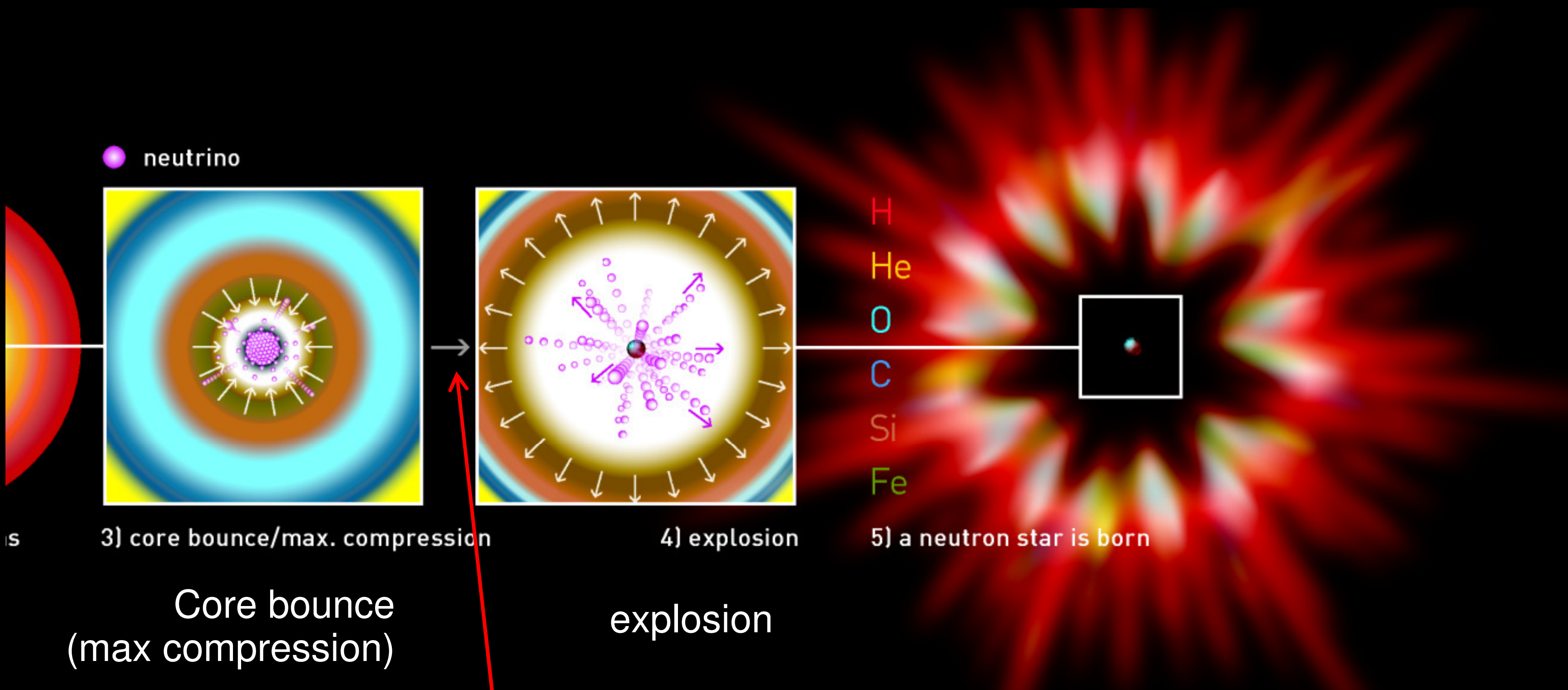
Core-Collapse Supernovae



Credit: Thielemann

H-burning	He-burning	C-burning	Ne-burning	O-burning	Si-burning
10^7 years	10^6 years	10^3 years	3 years	0.8 years	1 week

Core-Collapse Supernovae



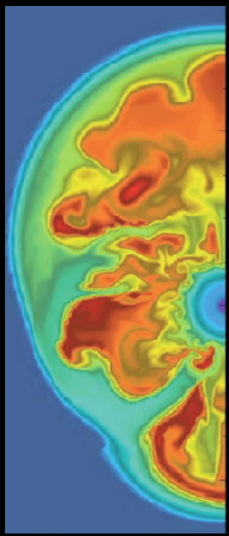
Core bounce
(max compression)

explosion

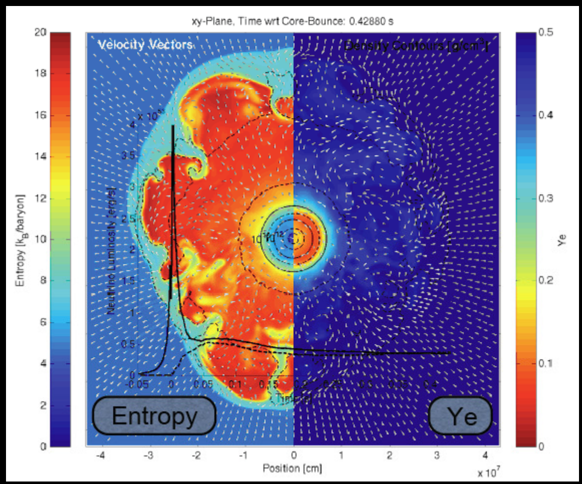
3D, SASI, acoustic modes, MHD, rotation, collective neutrino flavor oscillations, magic, ???

Simulations of Core-Collapse SNe

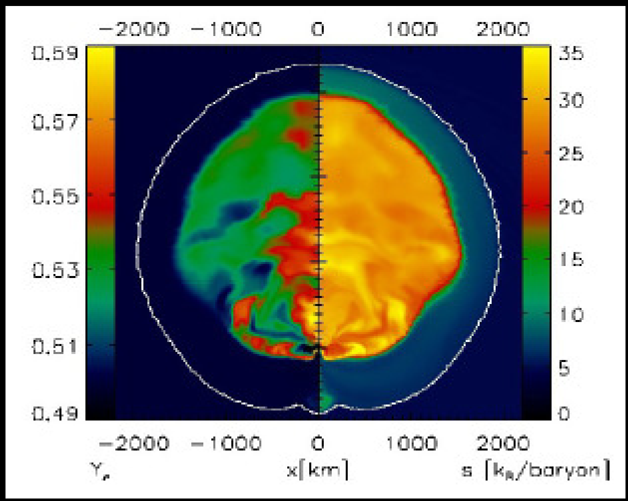
- No explosions in spherical symmetry (*)
- Many ongoing efforts in multi-D



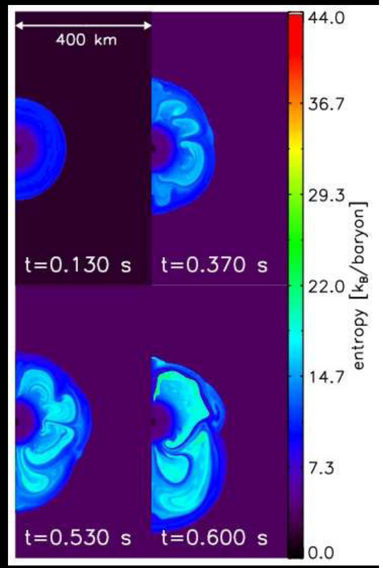
Oak Ridge



Basel



Garching



Princeton

⇒ Computationally expensive

⇒ But we still want to study supernova nucleosynthesis

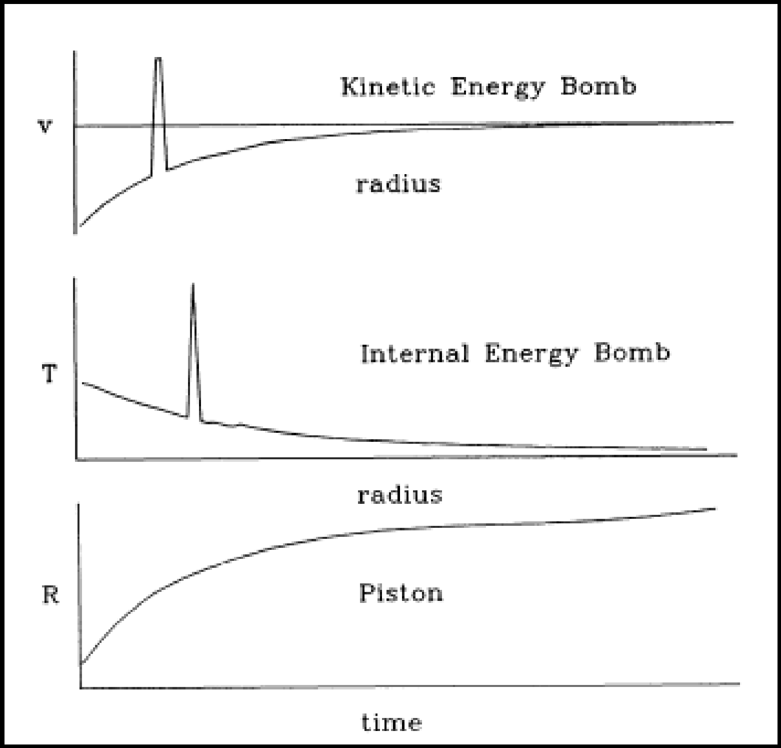
⇒ Artificial explosions

(*) except for ONeMg cores

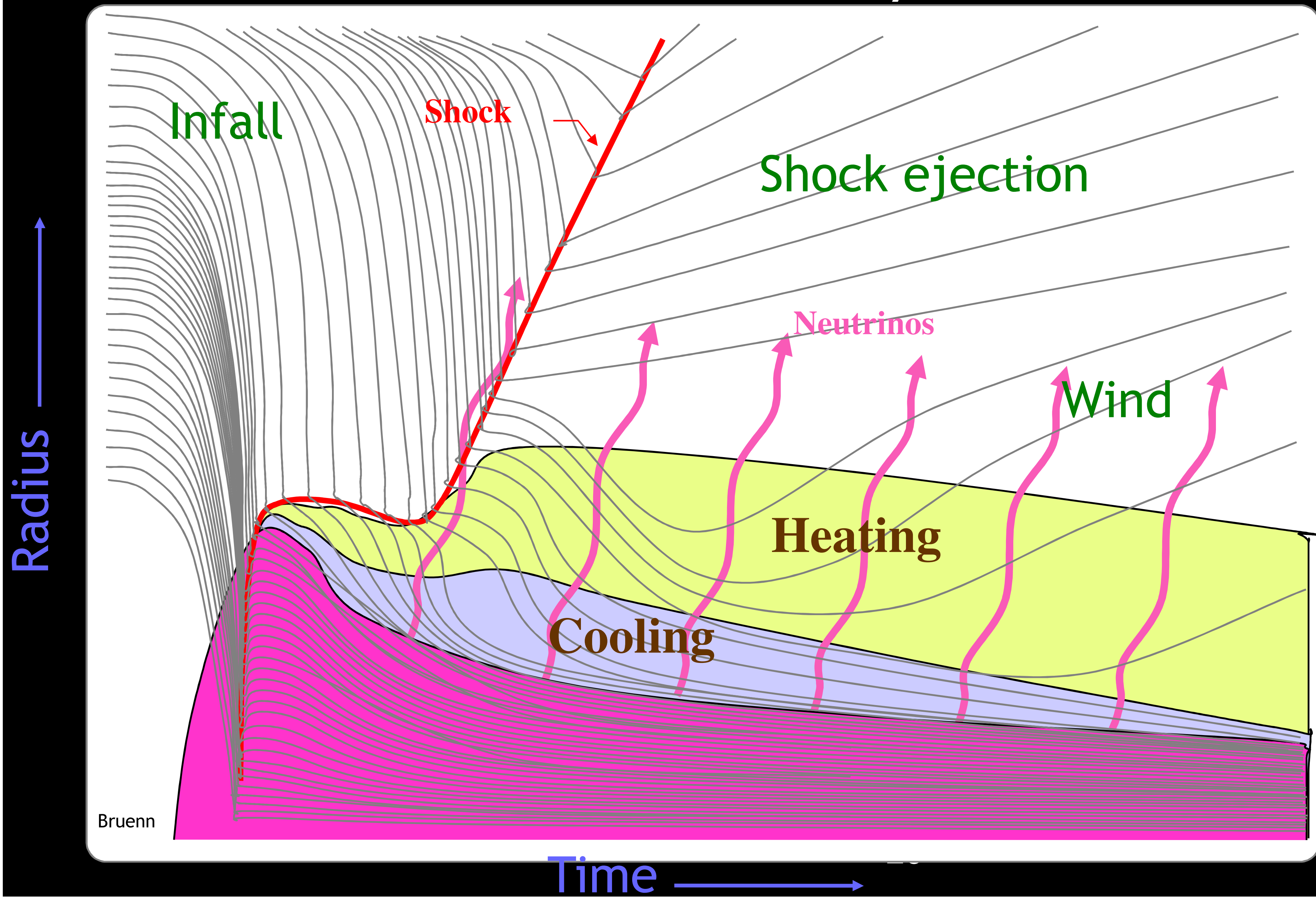
SN models for nucleosynthesis

In spherical symmetry need to artificially trigger the explosion:

1. Thermal bomb / piston: initiate explosion by increasing temperature or placing a piston in the star
   - Limitations: misses physics of collapse, bounce, and onset of explosion

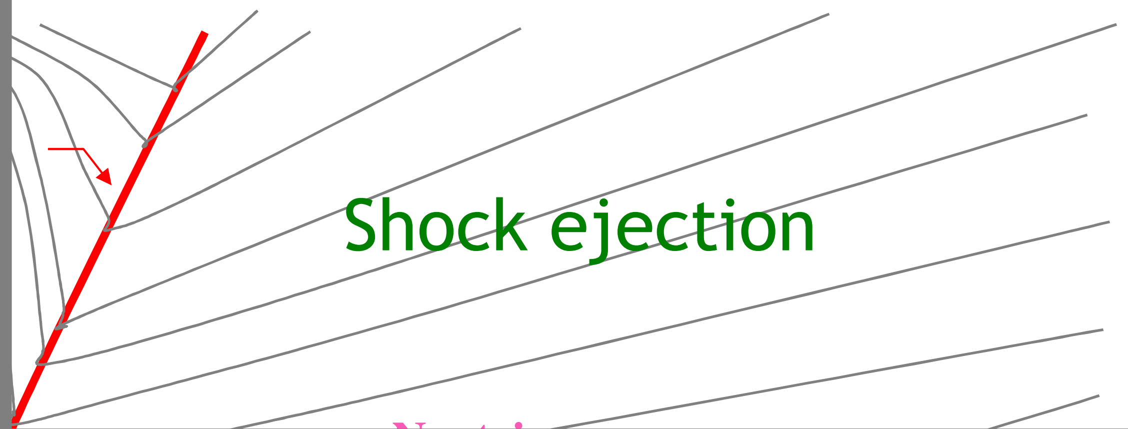


SN models for nucleosynthesis



Supernova Nucleosynthesis

What happens during collapse and bounce?
Electron fraction?
How has this material changed before it gets shocked?



Location of the mass cut?

Effect of neutrinos?

Effect of neutrinos

Supernova dynamics

- Deposit energy to revive stalled shock
- → neutrinos can be used to trigger a more realistic induced explosion

Neutron-to-proton ratio (electron fraction)

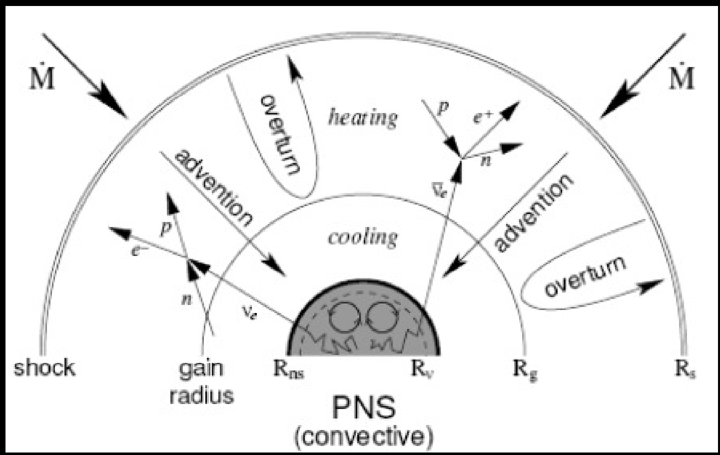
- Neutron-rich (r-process)
- Proton-rich (νp-process)
- → neutrino energies and luminosities are important

Neutrino-induced nucleosynthesis (νp-process; ν-process)

SN models for nucleosynthesis

2. Absorption: Mimics the effects of multi-D simulations in 1D
   - Convection in the heating region → more efficient energy deposition

$$\nu_e + \mathrm{n} \leftrightarrow e^- + \mathrm{p}$$
$$\overline{\nu}_e + \mathrm{p} \leftrightarrow e^+ + \mathrm{n}$$



   - Increased neutrino absorption and emission rates (in the heating region) by a constant factor
   - Limitations: large factors change the system beyond energy deposition

Effect of neutrinos

- Supernova dynamics
  - Deposit energy to revive stalled shock
  - → neutrinos can be used to trigger a more realistic induced explosion

- Neutron-to-proton ratio (electron fraction)
  - Neutron-rich (r-process??)
  - Proton-rich (νp-process)
  - → neutrino energies and luminosities are important

- Neutrino-induced nucleosynthesis (νp-process; ν-process)

Conditions in ν-driven winds

- Weak interactions set electron fraction Ye

$$\nu_e + \mathrm{n} \leftrightarrow e^- + \mathrm{p}$$
$$\overline{\nu}_e + \mathrm{p} \leftrightarrow e^+ + \mathrm{n}$$

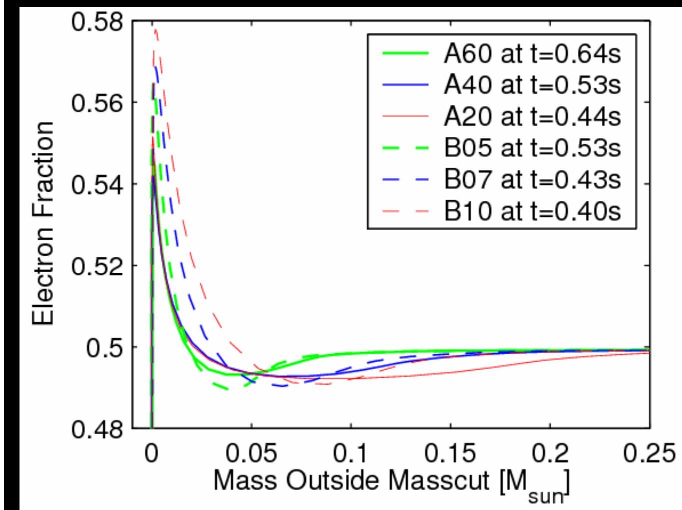
- R-process: high neutron-to-seed ratio (Y_n/Y_{seed} ~100)
  - Short expansion timescale (inhibits formation of seed nuclei)
  - High entropy (photons dissociate seed nuclei into nucleons)
  - Electron fraction Ye<0.5

- BUT: These conditions are not realized in recent simulations
  s/k_B ~ 50-120; τ ~ few ms; Ye ~ 0.4 – 0.6

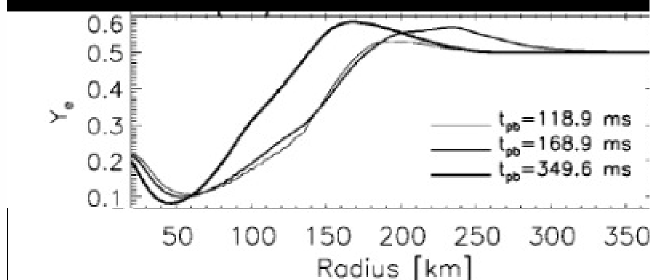
Neutron-to-proton ratio

Ye>0.5 is generic result of simulations with elaborate ν-transport

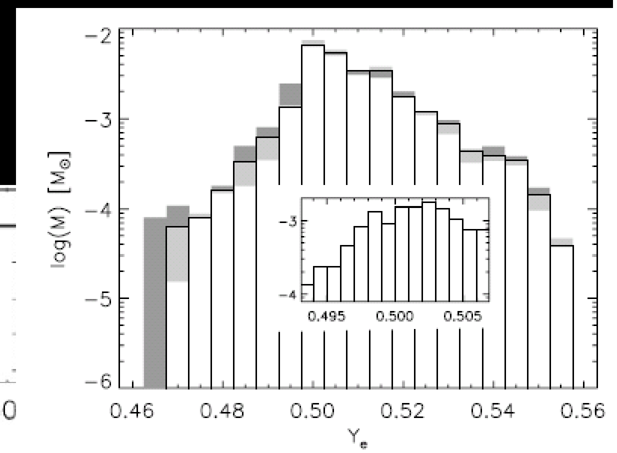
$$\nu_e + \mathrm{n} \leftrightarrow e^- + \mathrm{p}$$
$$\bar{\nu}_e + \mathrm{p} \leftrightarrow e^+ + \mathrm{n}$$



Liebendörfer et al (2001)
Frohlich et al (2006)



Rampp & Janka (2000)



Buras et al (2006)

- If the neutrino flux is sufficient (scales $1/r^2$):
- High density / low temperature → high E_F for electrons → e-captures dominate → n-rich
- If electron degeneracy lifted for high T → ν_e-captures dominate → due to n-p mass difference, p-rich composition

Effect of neutrinos

- Supernova dynamics
  - Deposit energy to revive stalled shock
  - → neutrinos can be used to trigger a more realistic induced explosion

- Neutron-to-proton ratio (electron fraction)
  - Neutron-rich (r-process??)
  - Proton-rich (νp-process)
  - → neutrino energies and luminosities are important

- Neutrino-induced nucleosynthesis (νp-process; ν-process)

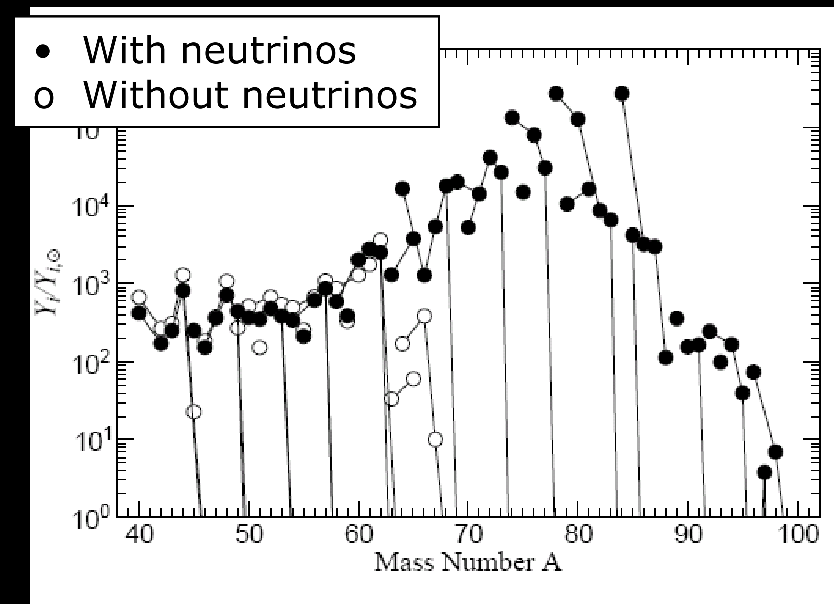
The νp-Process

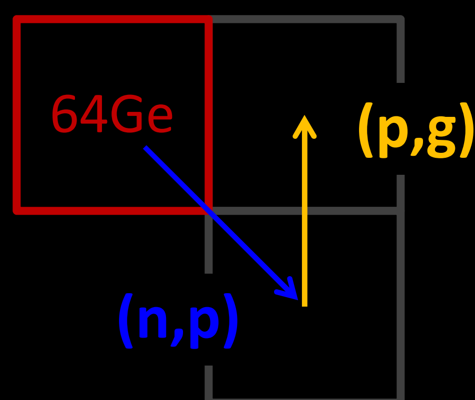
- proton-rich matter is ejected under the influence of neutrino interactions
- true rp-process is limited by slow β decays, e.g. τ(64Ge)
- Neutron source:

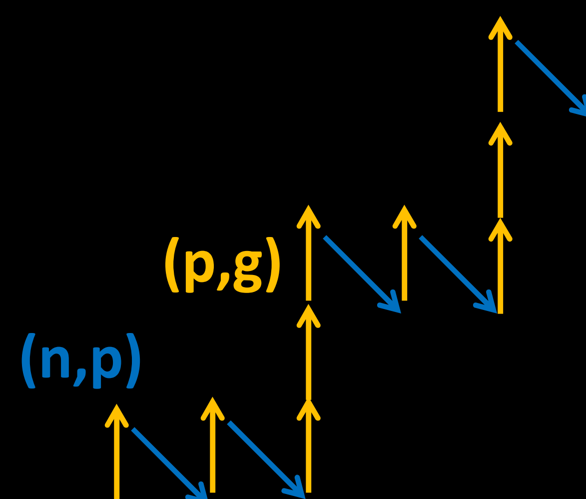
$$\overline{\nu}_e + p \rightarrow n + e^+$$

- Antineutrinos help bridging long waiting points via (n,p) reactions:

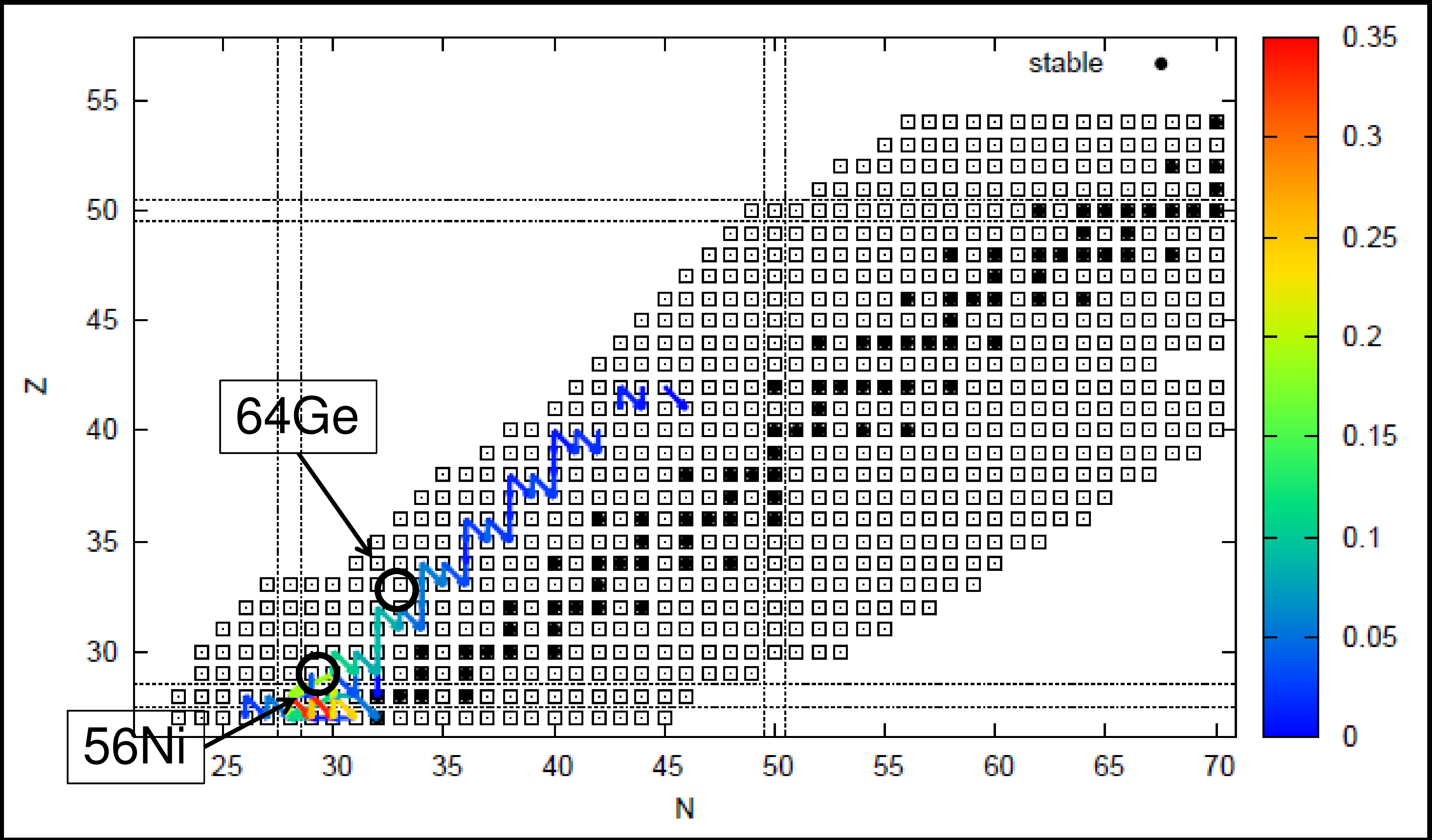
(n,p)
(p,γ)



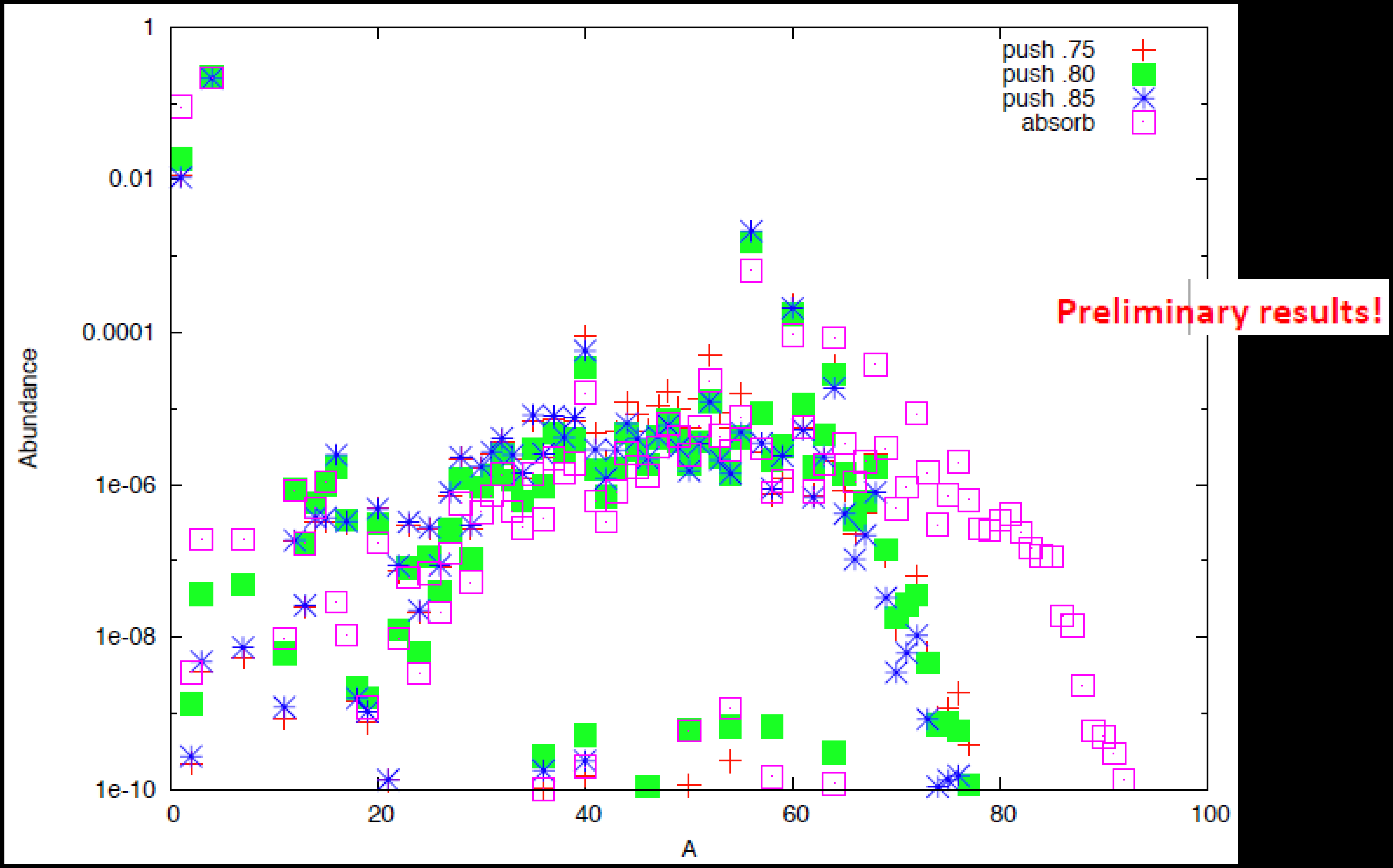




The νp-Process



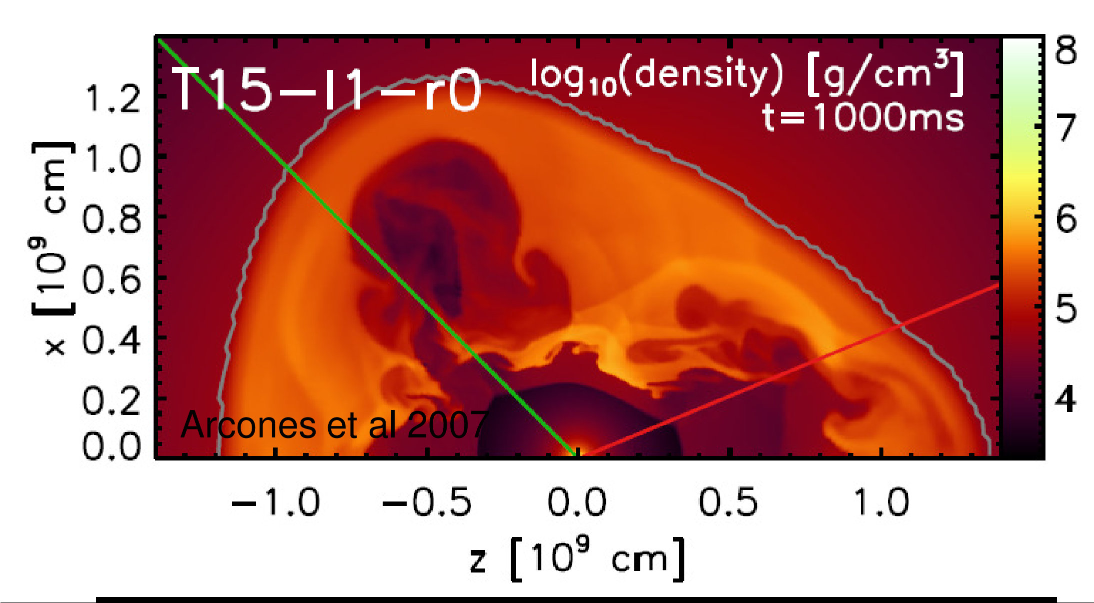
Nucleosynthesis

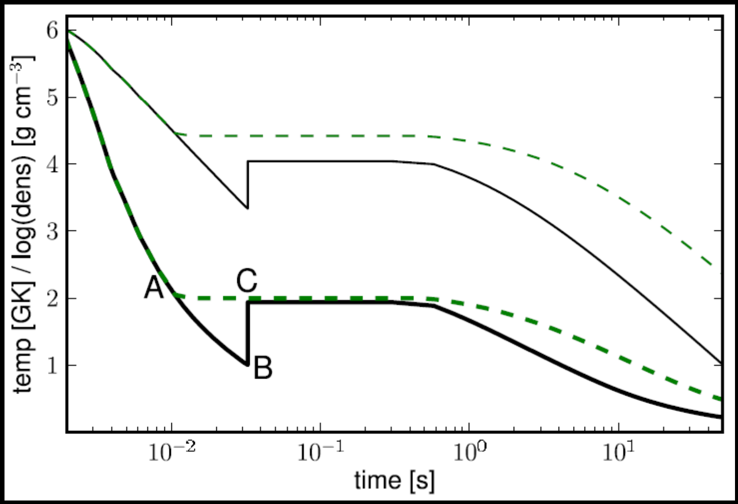


Melton & Frohlich

Wind termination shock

- Interaction of the neutrino-driven wind and the slow ejecta → wind termination shock
  - Deceleration and re-heating of material

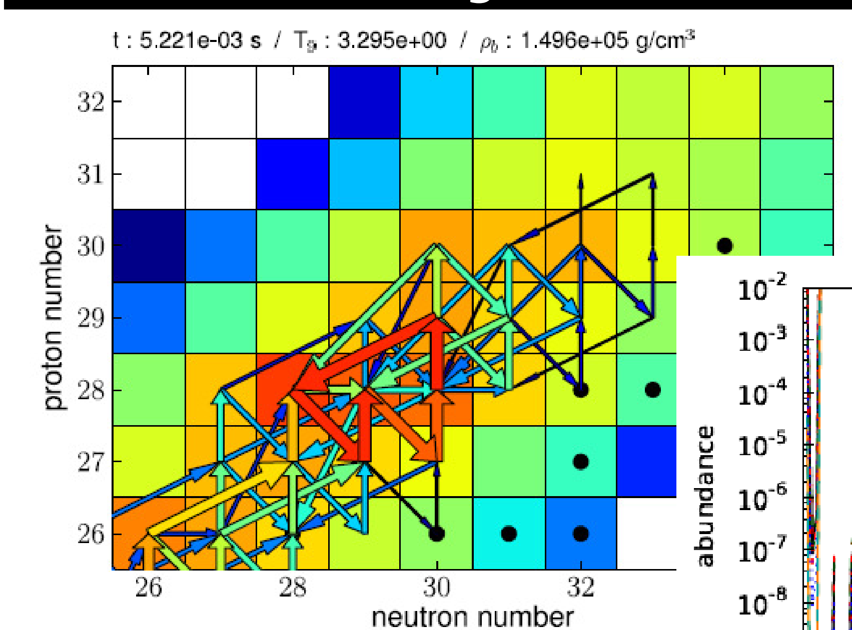


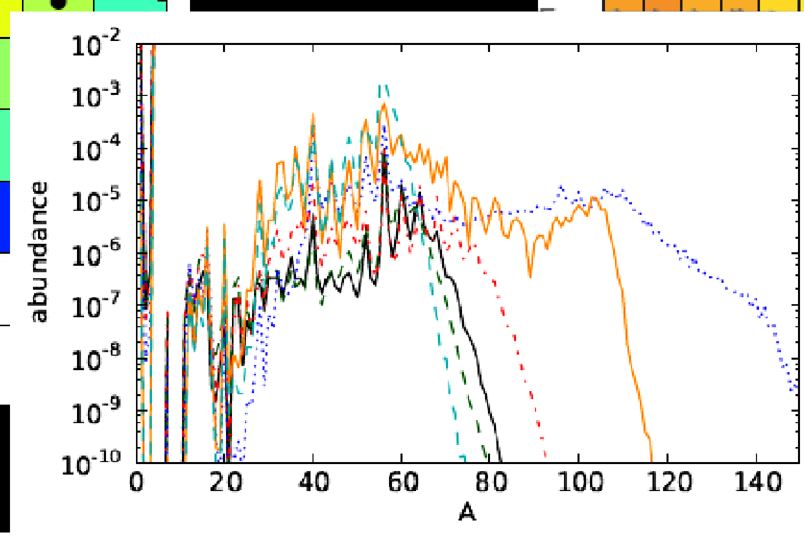


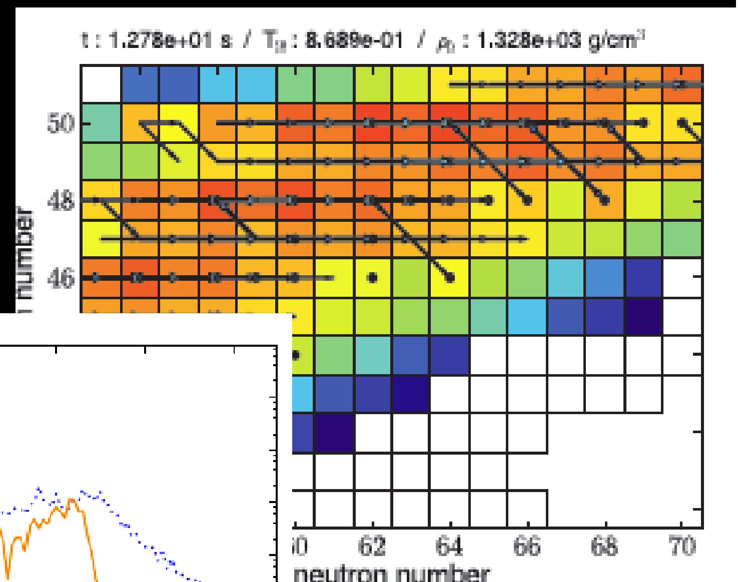
Long-term hydordynamical simulations:
2D: ~2ms – 3s p.b.
1D: ~2ms – 10s p.b.

Wind termination shock

- Effects of wind termination
  - T9>3 GK: matter stays in NiCu cycle
  - T9=2GK: heavier elements produced
  - T9<1GK: expansion too fast for neutrinos to produce enough neutrons



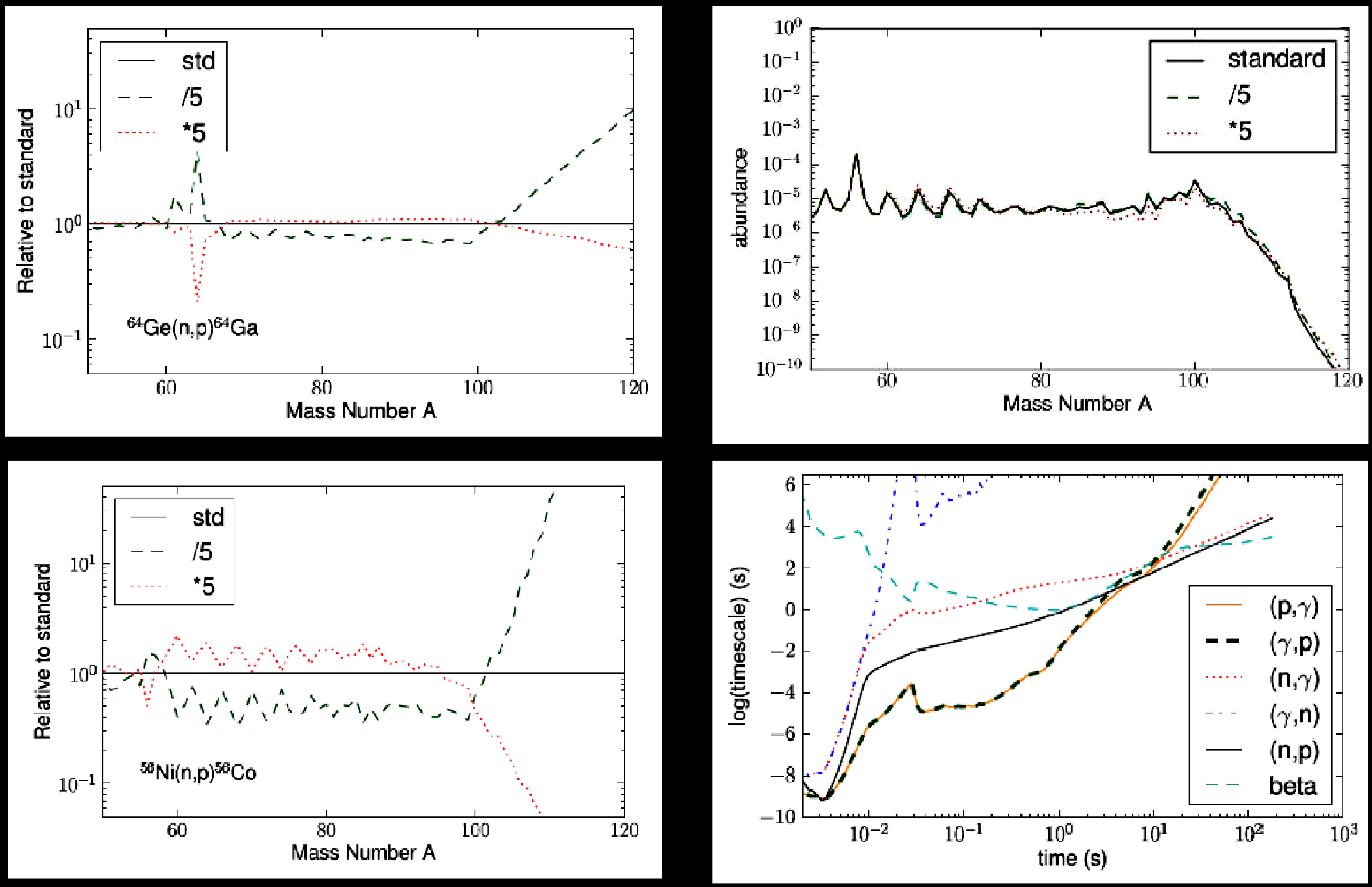




Arcones, Frohlich, Martinez (2012)

Critical (and not so critical) reactions

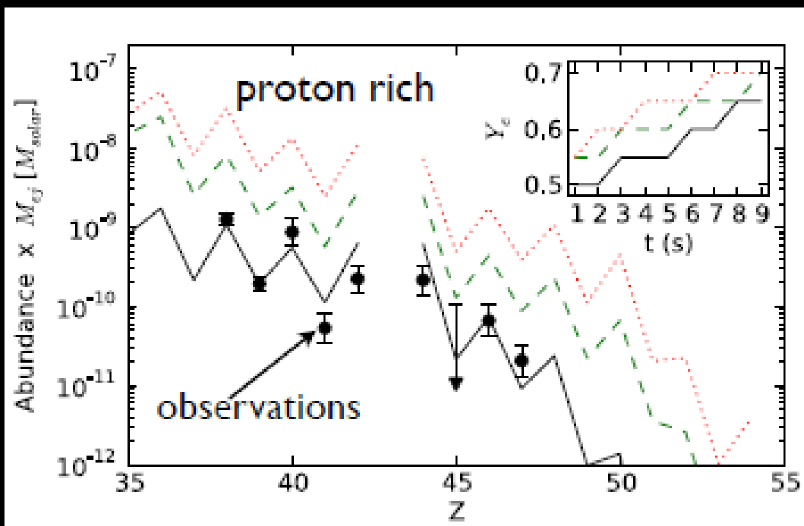
Frohlich et al (2012)



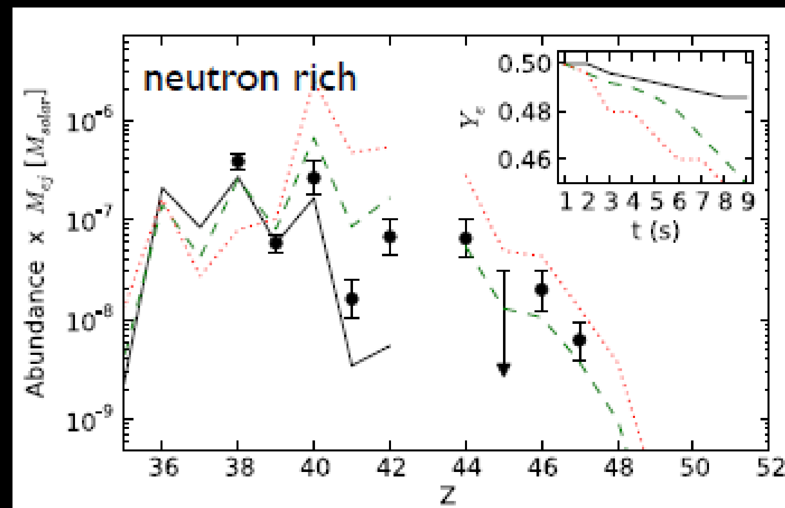
Electron fraction of the ejecta

- How does the abundance pattern from ν-driven wind simulations compare to the observed pattern in metal-poor stars.

Arcones & Montes (2011)



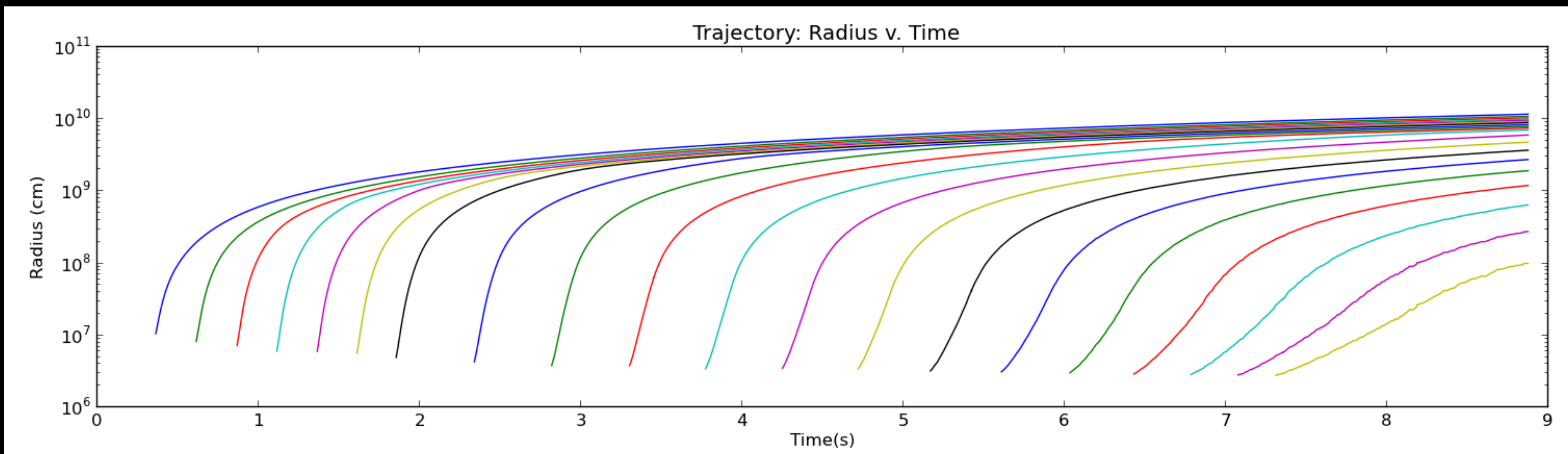
Observed pattern reproduced
Production of p-nuclei

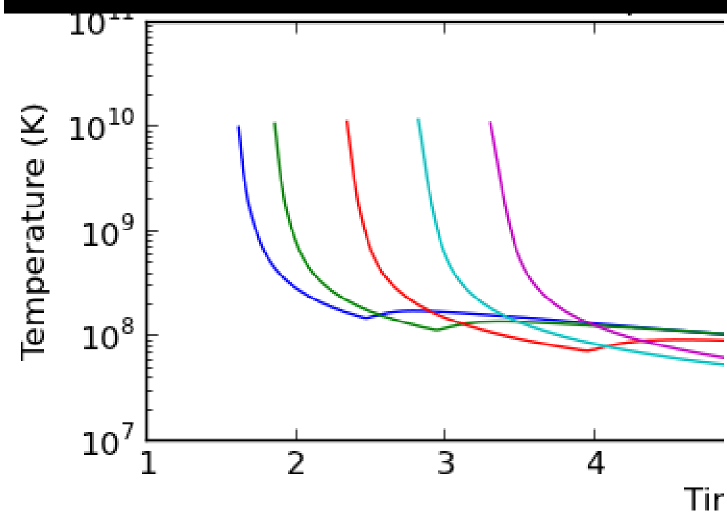


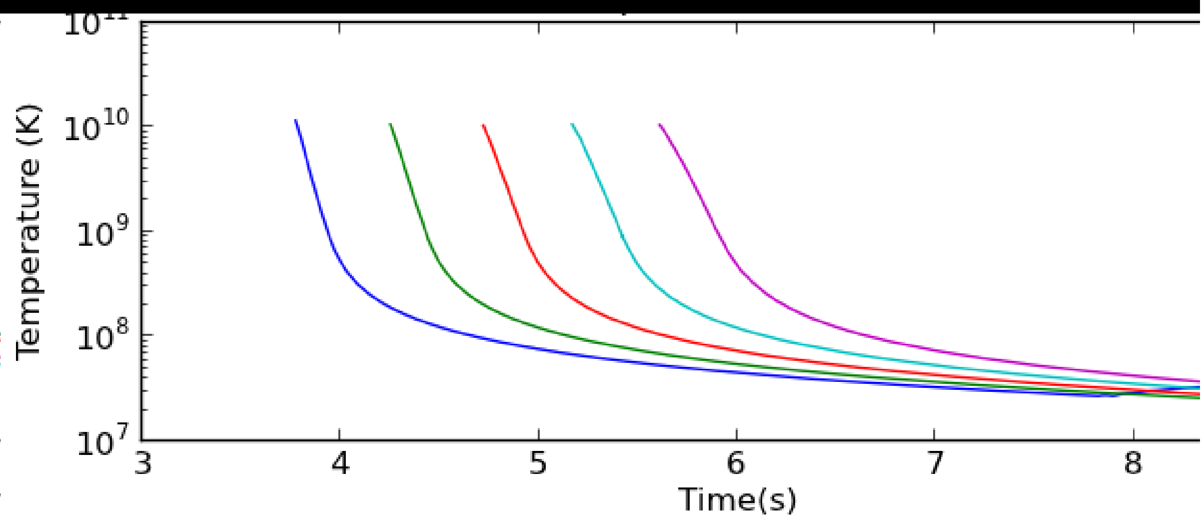
Overproduction of A=90 (N=50)
→ Only a fraction of neutron-rich ejecta (Hoffman et al 1996)

Neutrino Oscillations

8.8Msun model from Munich group:



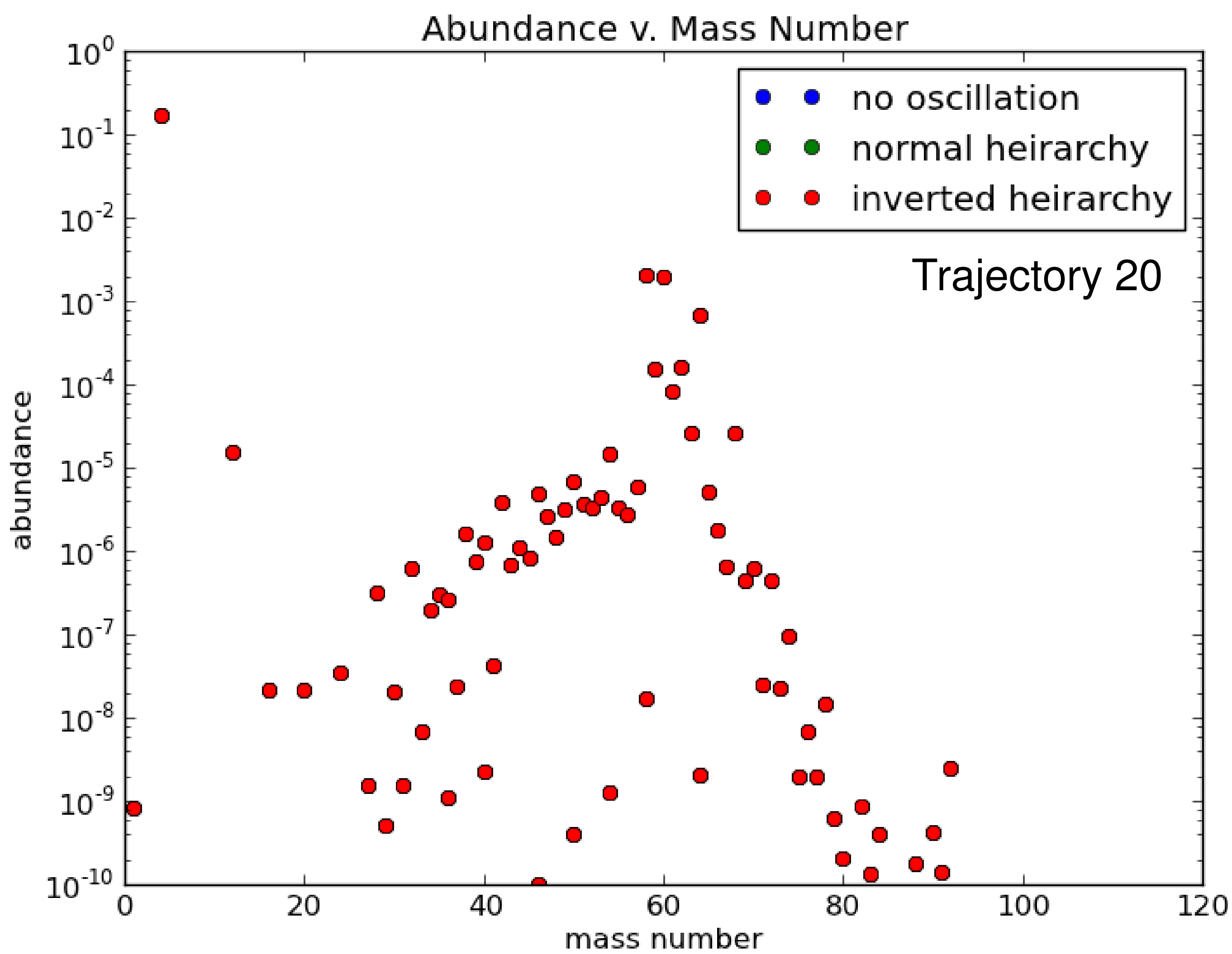




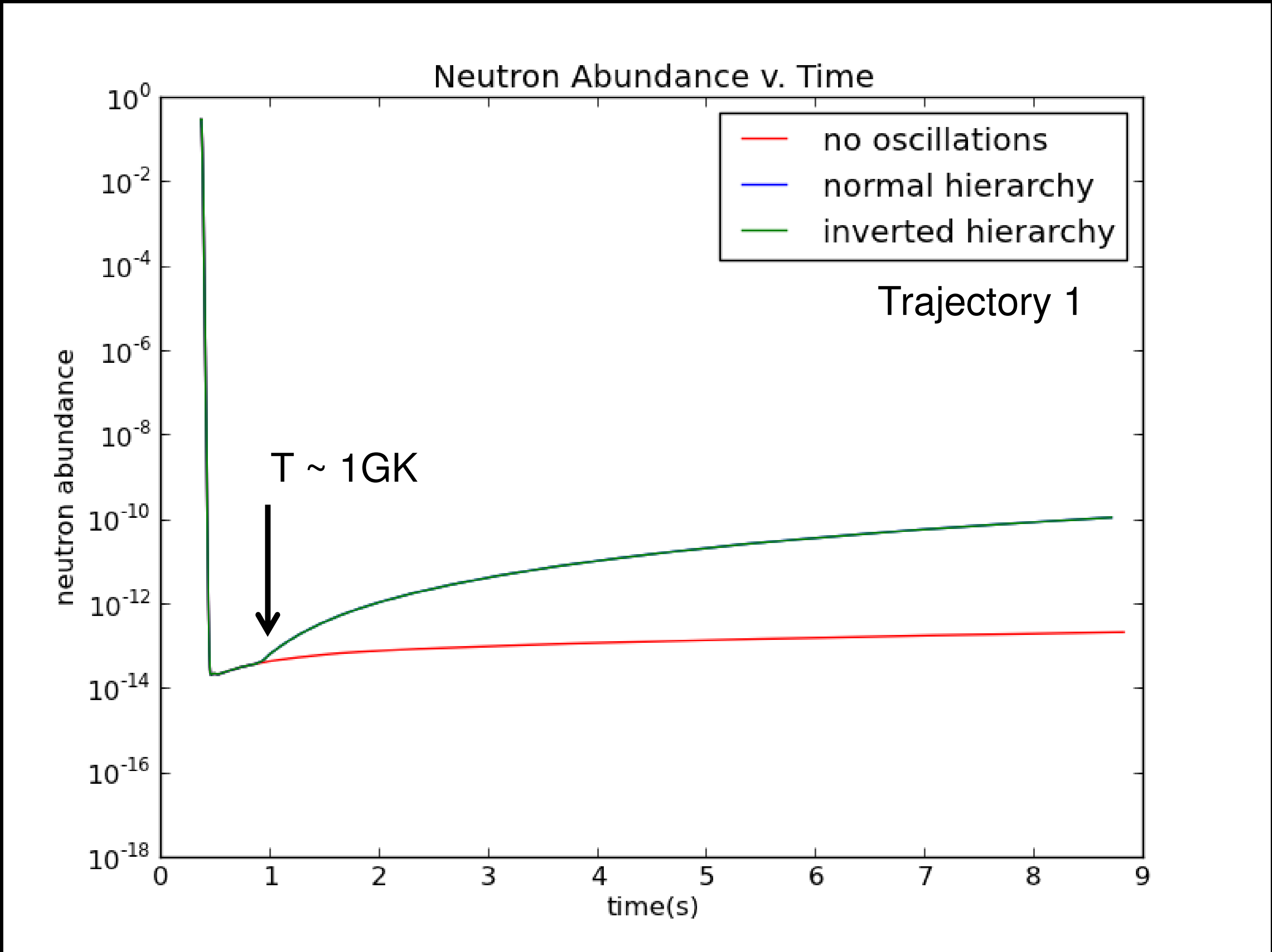
Neutrino Oscillations

- Supernova model: 8.8Msun — Huedepohl et al (2010)
- Rates for neutrino captures
  - Includes collective neutrino effects — Duan & Friedland
- Nucleosynthesis calculations — Seadrow & Frohlich

Neutrino Oscillations



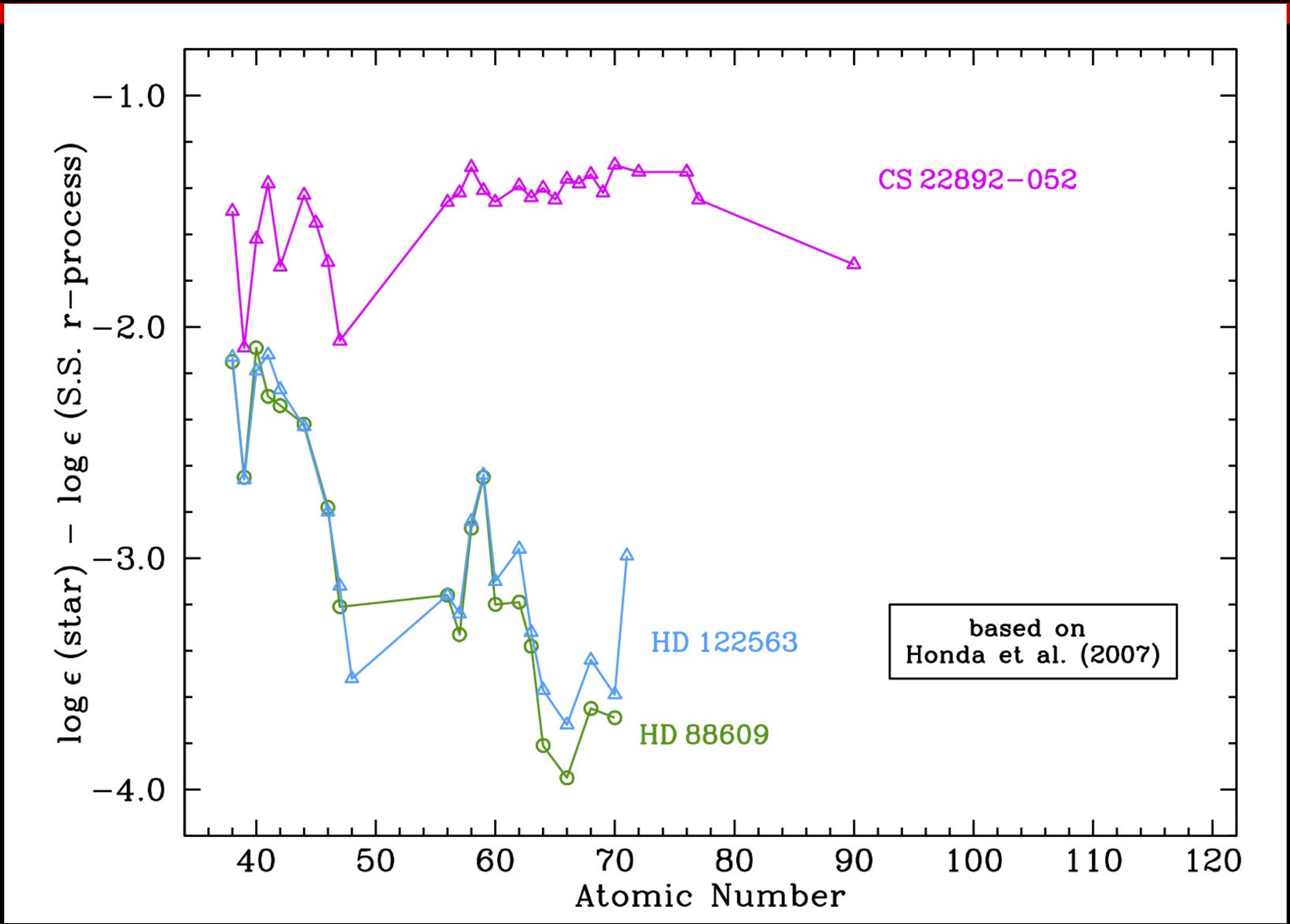
Neutrino Oscillations



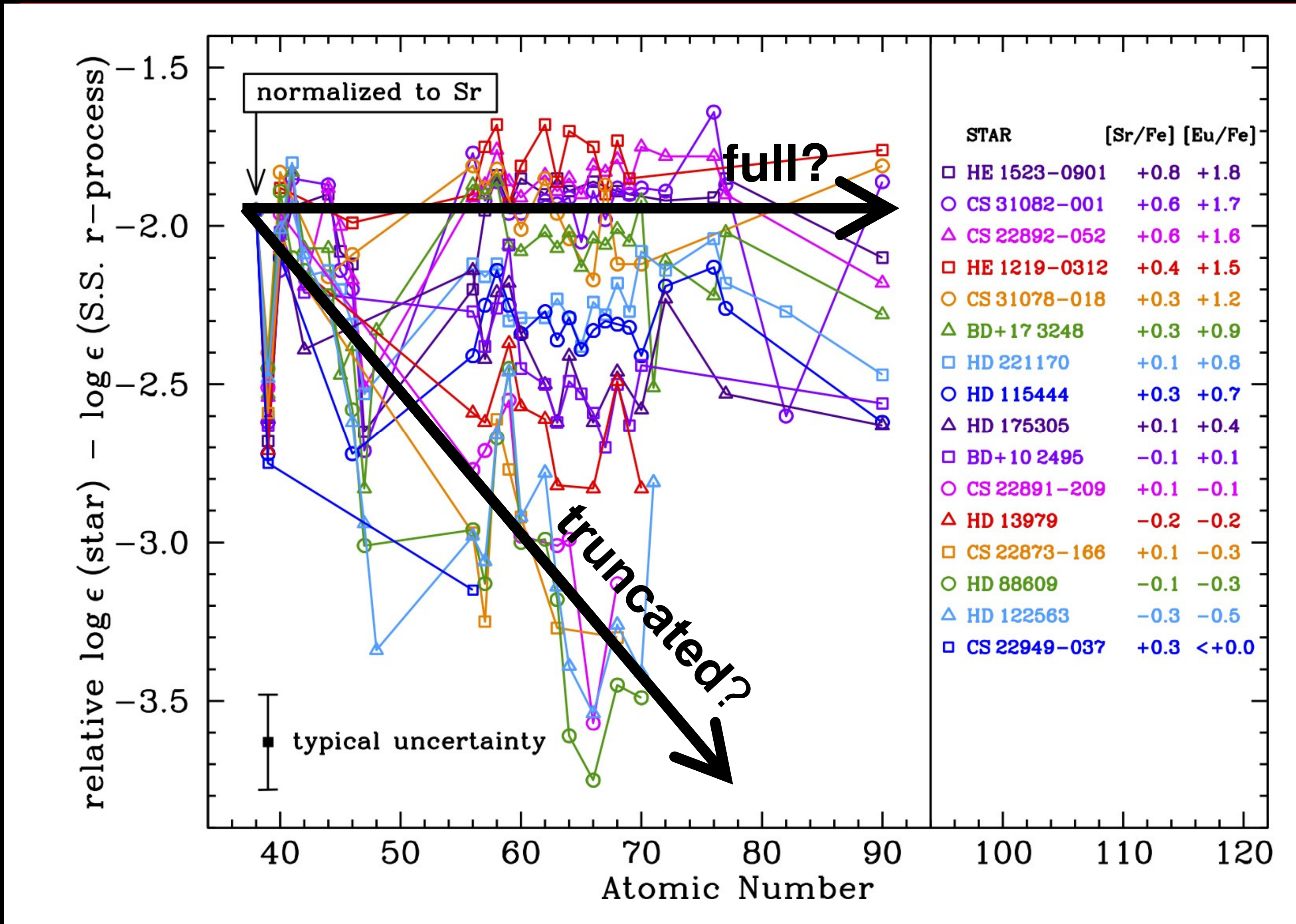
Summary & Conclusions

- Neutrinos are important for supernova dynamic and supernova nucleosynthesis
- Details set electron fraction and hence conditions for nucleosynthesis
- Observations indicate the need for an additional process (LEPP).
- The νp-process is a candidate for the LEPP.
- The νp-process nucleosynthesis depends on the detailed hydrodynamic conditions, nuclear physics, and neutrino physics.

Evidence for non-solar r-processes?



Roederer et al. 2010



Roederer et al. 2010